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A Computer Simulation Model for Analyzing Mobile Source Air Pollution Control Strategies

MATHTEC, Inc, Princeton, N J

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A COMPUTER SIMULATION MODEL FOR ANALYZING MOBILE SOURCE AIR POLLUTION CONTROL STRATEGIES

by

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LIST OF ABBREVIATIONS AND SYMBOLS

C-C-C or C-C	refers to round-trips whose origin and destination are both in the center of the city.
CO	carbon monoxide.
CS	consumers' surplus.
C-S-C or C-S	refers to round-trips whose origin is the center of the city and whose destination is outside the center.
HC	hydrocarbons.
I/M	inspection and maintenance of automobiles.
MATHAIR	MATHTECH's computer simulation model for evaluating air pollution control strategies.
NO_x	nitrogen oxides.
O-D	origin and destination.
OX	oxidants. MATHAIR predicts three different series: OX1, OX2, and OX3.
Pb	lead.
ppm	parts (of pollutant) per million parts (of air).
SO	baseline or zero control strategy.
S1	modest control strategy*.
S2	moderate control strategy*.
S3	moderate control strategy*.
S4 (S4.1, S4.2, S4.3)	strict control strategy with three variants*.

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* See Figure 8 for details.

LIST OF ABBREVIATIONS AND SYMBOLS (continued)

S-C-S or SC	refers to round-trips whose origin is outside the center of the city and whose destination is the center of the city.
SO_x	sulfur oxides.
S-S-S or S-S	refers to round-trips whose origin and destination are both outside the center of the city.
VMT	vehicle miles of travel.
VSAD	vacuum spark advance disconnect. A retrofit pollution control device for automobiles.

SECTION I

INTRODUCTION

The 1970 Amendments to the Clean Air Act required the establishment of specific national ambient air quality standards and a specific timetable for compliance with these standards. It also mandated specific, and substantial, reductions in automobile emissions, again by specified dates.

While this legislation attests to strong political support for air pollution control, its passage has not ended the debate over air quality standards. As is evidenced by the recently established more lenient interim air quality standards, it is clear that there will be continuing controversy over air pollution standards, and possible continuing changes in these standards.

Whatever the reason for this continued interest, it is useful to be able to evaluate alternative air pollution control strategies, in terms of both their impact on air quality and their dollar benefits and costs. Because the computations required to perform reasonably accurate evaluations are sufficiently complicated, a computer simulation model is needed for this purpose.

MATHTECH has developed a powerful and flexible computer simulation model, MATHAIR, that can be used to estimate the impact of strategies for controlling mobile source air pollution in terms of both the effect on air quality and the associated benefits and costs. To demonstrate how the model can be used, we applied MATHAIR to evaluating some selected air pollution control strategies in four urban areas.

SECTION II

SUMMARY

THE MATHAIR MODEL

The MATHAIR model enables the user to perform experiments evaluating the impact of air pollution control strategies in different geographic regions. For each strategy devised, MATHAIR calculates both the effect on air quality and the dollar benefits and costs associated with that strategy for a user-specified geographic region. These calculations are made relative to a baseline, or zero-control, strategy.

The effect of a pollution control strategy on air quality is calculated by first projecting the emission sources in a region and the level of emissions associated with each source. The impact of the control strategy on the level of emissions from each source is then calculated. Finally, an air quality model relates the changes in emission levels to changes in ambient air quality. Our attention is focused on controlling emissions of carbon monoxide (C)), hydrocarbons (HC), and oxides of nitrogen (NO_x). The principal emission source considered is automobiles; control measures considered affect air quality both by reducing emissions holding automobile use constant, and by reducing automobile use.

As regards the calculation of benefits and costs, the total cost for a strategy is taken to be the additional cost over that associated with the baseline strategy. Thus costs do not, for example, include the purchase price of automobiles but do include the extra capital and operating costs of pollution control devices.

In addition to direct costs, we also calculate the implied cost to travelers of reduced (or enhanced) mobility. The notion here is that certain strategies may reduce the number of automobile trips, and an imputed value of these foregone trips should be counted as a strategy cost.

To calculate the benefits of improved air quality resulting from air pollution control strategies, the damage due to air pollution is quantified in monetary terms for each control strategy. The benefit of a strategy is then calculated by subtracting those damages from the damages associated with the baseline, zero-control, strategy.

EXPERIMENTS PERFORMED WITH MATHAIR

In order to demonstrate the use of MATHAIR, four large urban regions were selected for the simulation experiments reported here: Los Angeles, New York, Washington, D. C., and Chicago. These regions provide a spectrum of the air quality problems found in large urban areas.

The air quality and damage results for the four regions, assuming zero controls, are reported in Section VI.

The simulation strategies analyzed here include (1) measures requiring the installation of pollution control devices directly on the source of pollution and (2) inducements to change patterns of transportation behavior. Examples of the first type include mandated installation of catalytic convertors on automobiles built after 1975 and required carbon adsorbers for hydrocarbons on all dry-cleaning plants. Examples of the second type include increasing the cost per mile of automobile travel by imposing a tax on gasoline and decreasing bus waiting times by operating additional buses.

Control strategies representing modest, moderate, and strict degrees of air pollution control were devised for our example experiments and are discussed in Section VII.

The impacts of the strategies on ambient pollution concentrations, presented in Section VII, are mixed and thus difficult to summarize. Even modest controls effect significant air quality improvements. However, Federal standards for some pollutants cannot be met even with our most stringent strategies. The benefits and costs of alternative strategies in the four study regions are presented in Section VIII. A moderate level of control proved optimal, in the sense of maximizing net benefits, in Los Angeles and Chicago. Very modest controls were best in New York while no controls was the optimal choice in Washington.

These results are, of course, dependent on the input data used. A limited sensitivity analysis, reported in Section IX, showed that certain inputs had a marked effect on model outcomes.

SECTION III

CONCLUSIONS

We believe that MATHAIR strategy simulations are a practical way to do policy analysis. MATHAIR provides a powerful, flexible framework for testing the impact of air pollution control.

Based on the numerical results of the experiments we have conducted with MATHAIR, a certain number of conclusions can be drawn.

GENERAL CONCLUSIONS

1. The first conclusion is suggested both by a priori considerations and by the numerical results: it is economically inefficient to impose the same program of controls in different regions. Different regions have different compositions of total emissions, different meteorological carrying capacities, and different transportation systems; and a flexible national policy that encourages exploitation of these differences could yield substantial economic benefits.

2. A second conclusion that emerges from our work is that the costs associated with changes to less preferred modes of transportation and reduction in trip frequency can be substantial and should not be omitted from a cost calculation. To be sure, there may be social benefits associated with these changes -- reduced congestion, less noise pollution, fewer accidents, and conservation of scarce fossil fuels -- as well as the air pollution reduction benefits that we account for in our calculations. Nonetheless, our results indicate that these other benefits may have to be large to offset the marginal costs of adding transportation controls to an existing program of moderate controls.

3. MATHAIR air quality predictions show that oxidant standards cannot be met by 1985 in any study region even with our most stringent strategy. Our strictest measures, including transportation controls, are needed to meet the carbon monoxide standards.

4. Inspection and maintenance of automobiles appears to be beneficial in all regions.

5. Strategies requiring hardware control devices for automobiles are most successful in regions where the average automobile is driven intensively.

6. Transportation controls discouraging use of the automobile are most successful, in conjunction with other measures, in regions with the greatest existing availability of common transportation.

7. A program consisting of transportation controls only appears to be beneficial though of limited impact.

SENSITIVITY ANALYSIS

We performed a limited sensitivity analysis of MATHAIR to determine which inputs have a critical effect on strategy outcomes. The first experiment, assuming an accelerated rate of removing automobiles from the stock, had a minimal effect on policy implications.

The second experiment simulated a set of "worst case" assumptions for Los Angeles: increased control device costs, low baseline dollar damages due to air pollution, and low estimates of the pollutant reduction efficiencies of automobile control devices. The combined impact of these assumptions was a dramatic decrease in net benefits.

The final sensitivity experiment simulated three versions of the strictest control strategy, each containing a different transporation control measure. The marginal cost of the strategy exceeded the marginal benefit in all cases.

SOME QUALIFICATIONS

Our results and conclusions are based on an amalgam of models, published data, and assumptions. To the greatest extent possible, we have relied upon inputs and methods that EPA has accepted for purposes of preparing implementation plans and transportation control plans. Nonetheless, it has been necessary to make many independent assumptions. For example, we have assumed that benefits of pollution control vary linearly with reductions in ambient concentrations of pollutants. Our results would be quite a bit different if we had assumed that benefits vary as (say) the square or the cube of concentration reductions. Many strategies that fail to produce positive net benefits under the linear benefits assumption would pass under nonlinear assumptions.

A portion of the data we have used to test the model was estimated by us. Even the data we have from public sources are subject to considerable uncertaintly. For example, recent studies suggest that the emissions control equipment is considerably less effective than is reflected in the EPA data we have used in our calculations. * Other things being equal, this factor tends to cause our calculations to overstate the net benefits of vehicular emissions control strategies.

In consequence, it must be concluded that the estimated costs and benefits associated with alternative mobile source pollution control strategies are very sensitive to the assumptions one makes. It will be possible to give more precise estimates of benefits and costs only as the uncertainty about inputs is reduced by further research on the basic scientific and technical aspects of air pollution control and by improving and updating data estimates.

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* U. S. Environmental Protection Agency, Compilation of Air Pollutant Emission Factors, AP42 (April 1973), and Supplement No. 2 (September 1973) vs. the preliminary edition of Supplement No. 5 (April 1975).

SECTION IV

RECOMMENDATIONS

In the course of developing MATHAIR, we used it to evaluate dozens of air pollution control strategies and found it a powerful and flexible analytic framework for policy analysis. We have only begun to explore the kinds of strategies that can be tested with MATHAIR, and while our results demonstrate the feasibility and potential usefulness of an integrated model for this purpose, we are also aware of the limitations of the approach and the weaknesses in our data base. Our recommendations are itemized below:

- A model like MATHAIR should be widely used to evaluate likely policy impacts in urban areas prior to the adoption of control measures at the state, regional, or Federal levels.
- More recent and more carefully estimated data are needed for use with MATHAIR than the data used for the test runs. The first priority for further work using the MATHAIR model is to improve the data base.
- A particular data need is for improving parameter estimates for the Transportation Module of MATHAIR.
- Module-by-module validation of MATHAIR predictions is needed.
- More extensive analysis of MATHAIR's sensitivity to changes in the data should be performed.
- As more research is done on damage functions, this information should be incorporated into the Benefits Module of MATHAIR.

SECTION V

OVERVIEW OF THE MATHAIR MODEL

INTRODUCTION

This section outlines MATHAIR, the model developed by MATHTECH to estimate the costs and benefits of alternative strategies for improving air quality. This section is intended to give the reader an overview of the model; a more extensive discussion of MATHAIR is presented in Appendix B.

A flow diagram of MATHAIR is shown in Figure 1.

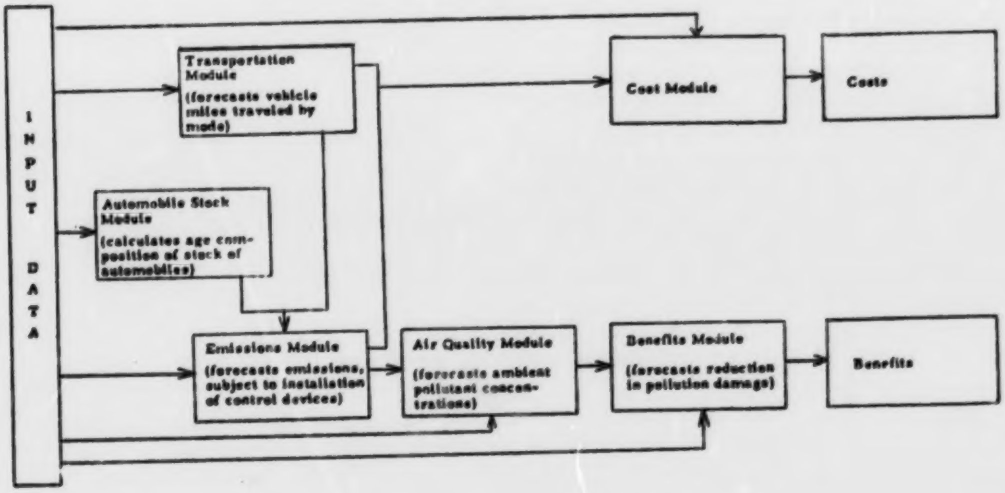
INPUT DATA
Transportation Module (forecasts vehicle miles traveled by mode)
Automobile Stock Module (calculates age composition of stock of automobiles)
Emissions Module (forecasts emissions, subject to installation of control devices)
Air Quality Module (forecasts ambient pollutant concentrations)
Benefits Module (forecasts reduction in pollution damage)
Benefits
Cost Module
Costs

Figure 1. A flow diagram of MATHAIR.

MATHAIR consists of the following six modules:

1. Automobile Stock Module, which computes the composition of the automobile stock.

2. Transportation Module, which forecasts vehicle miles of travel for each mode of transportation.

3. Emissions Module, which calculates pollution emissions for mobile sources and stationary sources subject to the installation of control devices.

4. Air Quality Module, which calculates the ambient concentrations of the pollutants.

5. Benefits Module, which calculates dollar losses due to pollution damage and the benefits (i.e., reduction in losses) with respect to a baseline case.

6. Cost Module, which calculates the cost of implementing the control strategy.

All region-dependent information is contained in the input data so that no adjustments to MATHAIR are required to run the model for different urban areas. Input files can, of course, be changed or updated.

AUTOMOBILE STOCK MODULE

The inputs for this module are historical new car registrations, predicted annual growth rate for new car registrations, and a schedule of scrappage rates which specifies the percent of automobiles of each age (one year old, two years old, etc.) that are removed from the automobile stock. This information is used to calculate the number of automobiles of each age on the road in each simulation year.

TRANSPORTATION MODULE

A flow diagram of the Transportation Module is given in Figure 2. It predicts trips by mode (automobile, bus, or rail), purpose (work, shop, other), and spatial pattern (center-center, suburb-suburb, center-suburb, suburb-center).

For each type of trip, the module requires the following inputs:

- average time and out-of-pocket costs *
- number of "potential" trips
- average trip distance

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* Out-of-pocket costs are the costs incurred for an additional trip. For automobile trips this includes the cost of gasoline, parking, and tolls but does not, for example, include payments for the automobile or the cost of insurance.

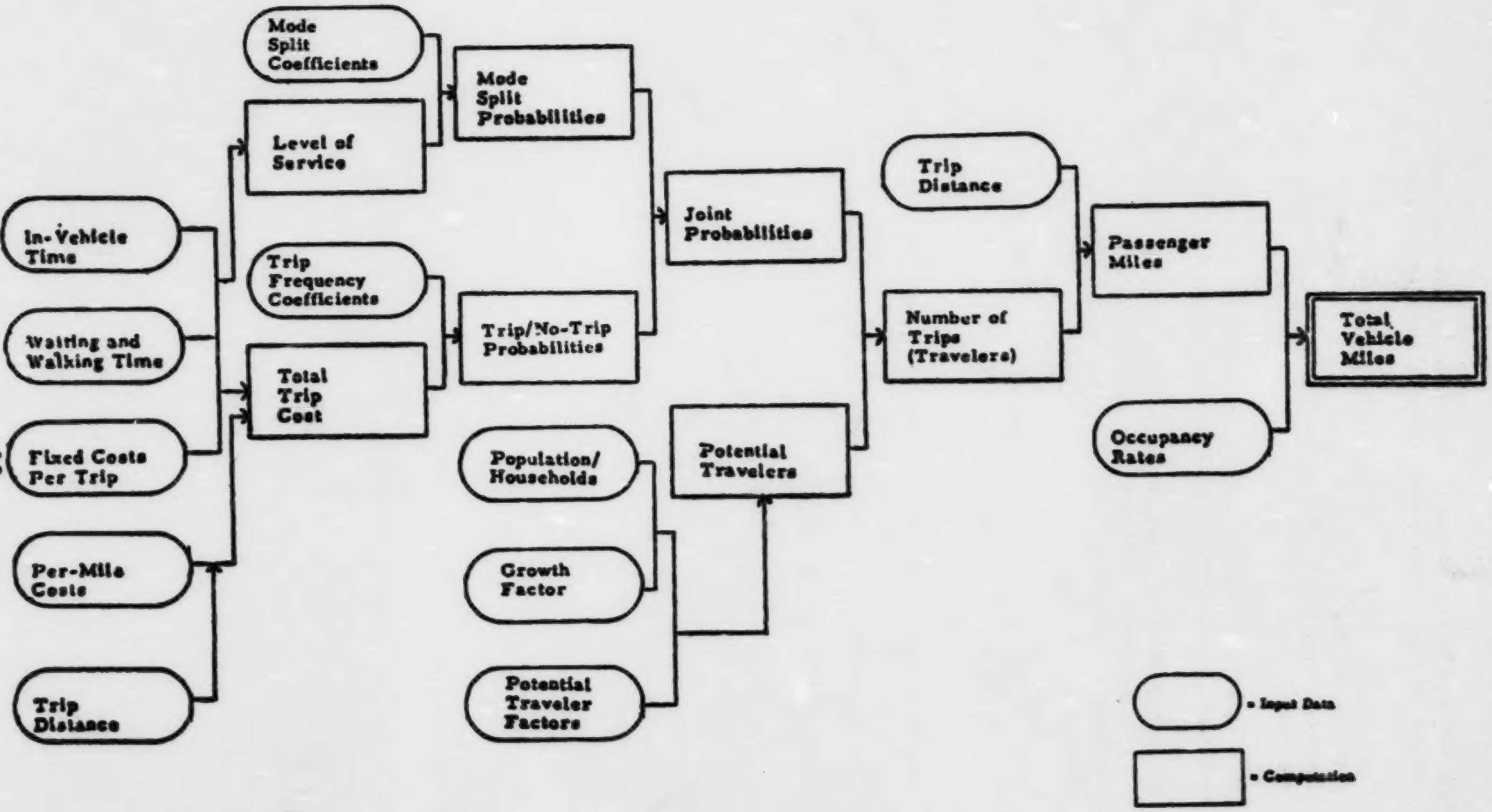

Figure 2. A Flowchart of the Transportation Module

- average vehicle occupancy
- base year vehicle miles traveled

These inputs are used to compute vehicle miles traveled by each mode. Based upon time and out-of-pocket costs associated with each kind of trip, the model predicts mode-choice probabilities and trip frequency probabilities whose product is the joint probability of taking a trip by a given mode between a given origin and destination. The joint probability is then multiplied by the number of potential trips between that origin and destination to produce an estimate of passenger trips, by mode. Then trip distance and vehicle occupancy data are used to calculate vehicle miles of travel (VMT). Region-wide base year VMT predictions are calibrated to base year data.

The user has the option of bypassing the transportation model and reading in base year VMT and an annual growth rate.

Alternative Structures Considered

Our principal requirement for the transportation model was that demand be sensitive to the policy variables: the time and out-of-pocket costs of taking a trip. This requirement ruled out the use of Urban Transportation Planning models, like the travel demand submodel of TASSIM. * In these models the number of trips demanded is determined by socio-economic factors in the zone of origin, not by the level of service. A model like TASSIM cannot evaluate the effect on demand of changed trip costs.

We also considered using the transportation model developed by RAND for the San Diego Clean Air Project and subsequently recalibrated for Los Angeles. ** We decided against this for several reasons. For example, no user documentation had been prepared for the model. Another drawback was that no spatial disaggregation (i.e., between city center and the outlying area) is possible in the RAND model since trips are characterized only by their origin and their distance.

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* Ingram, G.K., and G.R. Fauth, TASSIM: A Transportation and Air Shed Simulation Model, U.S. Department of Transportation (May 1974).

** Goeller, B.F. et al, San Diego Clean Air Project, The RAND Corporation, R-1362-SD, (December 1973). Also, Mikolowsky, W.T. et al, The Regional Impacts of Near-Term Transporation Alternatives: A Case Study of Los Angeles, The RAND Corporation, R-1524-SCAG (June 1974).

It should be noted that the MATHAIR Transportation Module is a demand model, with the number of miles traveled for each mode assumed equal to the amount demanded; no allowance is made for supply constraints. In the case of automobile travel, this limitation presents no difficulty, since none of the policies considered here increases automobile use. Therefore, the existing stock of automobiles, highways, etc., should be adequate to meet demand for predicted automobile travel. As regards buses, it is implicitly assumed in the present version of MATHAIR that the supply of buses will expand to meet increased demand for bus travel. This assumption is less realistic but does enable us to investigate what would happen if there were no restrictions on the availability of mass transportation.

Finally, it should be noted that while the Transportation Module has the structure of a disaggregated behavioral model, * we have used aggregated input data with a disaggregated model thus introducing some bias into our predictions. The nature of the bias is discussed in Appendix C.

EMISSIONS MODULE

The Emissions Module predicts total annual emissions from the stock of automobiles and other mobile sources and from stationary sources. Predictions are made for the so-called "mobile source" pollutants carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x), sulfur oxides (SO_x) ** and lead particulates (Pb). *** The module also simulates the effects of installing air pollution control devices.

Automobile Emissions

The emissions of an individual automobile are assumed to be proportional to miles traveled (with an adjustment for speed). The Emissions Module calculates the number of miles driven by automobiles of each age for each simulation year. This calculation requires three inputs: the age composition of the stock of automobiles (provided by the Automobile Stock Module), automobile vehicle miles traveled (provided by the Transportation Module), and the percent of all automobile miles driven by automobiles of each age (a user-provided input to the Emissions Module).

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* Disaggregated behavioral demand models are described in detail in Domencich, T.A. and D. McFadden, A Disaggregated Behavioral Model of Urban Travel Demand, Cambridge, Mass., Charles River Associates, Inc. (March 1972).

** All oxides of sulfur are treated as a single pollutant in MATHAIR since there is not yet sufficient quantitative information to separately model the quantities and effects of SO_2 and SO_3.

*** The lead content of fuel is a user-specified variable.

The required input data include automobile emissions, in grams per mile traveled, for each of the mobile source pollutants. These emission factors are available for new automobiles (of different vintages) driven at a standard speed. "Deterioration factors," which specify the rate at which emissions increase as automobiles age, are then used to compute emissions for old automobiles. Finally, estimated average automobile speeds and speed correction factors are needed to adjust emission factors for the difference between standard speeds and the speed assumed in the simulation.

A final input required by the automobile section of the Emissions Module are estimated efficiencies of various pollution control devices.* The installation of control devices is simulated as a percent reduction in automobile emissions.

Other Mobile Sources

Bus emissions are calculated as the product of a bus emissions factor and annual miles traveled by bus. An inventory of emissions from other mobile sources (e.g., motorcycles) may also be provided as input at the user's option. In the current version of MATHAIR, no air pollution control devices can be installed on mobile sources other than automobiles.

Stationary Sources

An inventory of stationary air pollution sources must be input to the module. The number of "average-sized" units and emissions of each pollutant for an average unit must be provided for each type of source. Emissions are calculated as the product of the number of units and emissions per unit. The installation of control devices is simulated as a percent reduction in predicted emissions.

AIR QUALITY MODULE

We selected a simple linear rollback model for predicting air quality. The formulation is based on the assumption that ambient pollutant concentrations are proportional to total emissions. Although this approach fails to exploit information about spatial and temporal diffusion of pollution, the rollback model seems an adequate approximation for assessing broad classes of strategies based on inter-regional comparisons. The inputs to the module are rollback coefficients, which are exogenously estimated for each pollutant using data on pollution emissions and concentrations for some base year, and estimates of emissions for each simulation year (provided by the Emissions Module).

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* Up to one hundred control devices can be defined without altering the computer program.

The required input data include automobile emissions, in grams per mile traveled, for each of the mobile source pollutants. These emission factors are available for new automobiles (of different vintages) driven at a standard speed. "Deterioration factors," which specify the rate at which emissions increase as automobiles age, are then used to compute emissions for old automobiles. Finally, estimated average automobile speeds and speed correction factors are needed to adjust emission factors for the difference between standard speeds and the speed assumed in the simulation.

A final input required by the automobile section of the Emissions Module are estimated efficiencies of various pollution control devices.* The installation of control devices is simulated as a percent reduction in automobile emissions.

Other Mobile Sources

Bus emissions are calculated as the product of a bus emissions factor and annual miles traveled by bus. An inventory of emissions from other mobile sources (e.g., motorcycles) may also be provided as input at the user's option. In the current version of MATHAIR, no air pollution control devices can be installed on mobile sources other than automobiles.

Stationary Sources

An inventory of stationary air pollution sources must be input to the module. The number of "average-sized" units and emissions of each pollutant for an average unit must be provided for each type of source. Emissions are calculated as the product of the number of units and emissions per unit. The installation of control devices is simulated as a percent reduction in predicted emissions.

AIR QUALITY MODULE

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* Up to one hundred control devices can be defined without altering the computer program.

Air quality, expressed in terms of pollutants on a parts per million parts of air basis, * is calculated as the product of the rollback coefficient and predicted emissions.

It is possible to modify the simple rollback model to allow for different coefficients for mobile and stationary source emissions. ** If the user selects this option, predicted air quality is a sum with two components: the product of the mobile source coefficient with mobile source emissions and the product of the stationary source coefficient with stationary source emissions.

BENEFITS MODULE

The Benefits Module calculates the monetary value of reduced damage and damage avoidance costs from air pollution control measures. In the simulations reported here, three damage categories are used: health, vegetation, and materials. However, the user may specify up to eight damage categories.

The module predicts the dollar value of air pollution damage, for a given pollutant and damage category, by evaluating damage functions of the following form:

$$D = \begin{cases} \delta(E-T)^{\gamma} & \text{if } E \geq T \\ 0 & \text{otherwise} \end{cases}$$

where D = dollar value of damages

E = air quality

δ = calibration constant

γ = user-specified exponent

T = air quality threshold below which no damage is assumed to occur.

The Benefits Module calculates the calibration coefficient in the following manner: the user specifies values of monetary damages, D_o, and pollutant level, E_o, for a base year, as well as estimates of γ and T. ***

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* This unit is known as ppm. Lead particulate is measured in $\mu g/m^3$.

** A discussion of why different coefficients might be appropriate is provided in Appendix D.

*** If the latter two parmeters are not specified, default values of $\gamma = 1$ and $T = 0$ are used.

One calibration coefficient δ is then computed for each damage category for each pollutant according to the formula

$$\delta = D_o/(E_o - T)^{\gamma}.$$

The estimated damages are summed over all damage categories for each pollutant, and the discounted present value is calculated. The benefit attributable to an air pollution control strategy is the reduction in pollution damage with respect to the damage associated with zero controls. This reduction can be estimated as the difference between the dollar value of the resulting pollution damage and the dollar value of pollution damage in the case of no controls. The two dollar values are calculated by MATHAIR in separate simulations, and the user must perform the subtraction manually. For ease of exposition, however, we discuss the Benefits Module as if it performed the subtraction and calculated for each strategy the dollar value of benefits.

Finally, the user has the option of replacing the Benefits Module with his own FORTRAN subroutine.

COST MODULE

The purpose of the Cost Module * is to calculate the total costs associated with implementing a strategy. These include the costs associated with air pollution control devices and the costs of changes in travelers' mobility.

To calculate the costs associated with air pollution control devices, the Cost Module requires as input unit costs and expected economic lifetimes for pollution control devices and the number of each device installed (from the Emissions Module). Unit costs include the initial cost of the device and annual maintenance and operating costs. The module calculates the present discounted value of the annualized initial cost of automobile and stationary source control devices. It also calculates the present discounted value of annual operating and maintenance costs and the cost of changed gasoline consumption due to automobile control devices.

A second type of cost is incurred when a traveler abandons his preferred mode of transportation and either switches to a less convenient mode or foregoes the trip altogether. Analogously, a benefit (negative cost) should be counted when a strategy induces a trip that would not otherwise have been taken. Using the number and prices of different types of trips (obtained from the Transportation Module), the Cost Module calculates the cost to travelers of reduced (or enhanced) mobility

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* Cost calculations are distributed throughout MATHAIR. It is, however, convenient to think of a single module that performs all the cost calculations.

due to transportation control measures. * Calculation of these costs is a unique feature of our analysis. **

Certain costs attributable to an air pollution control strategy are in fact changes in cost that can only be calculated with respect to a baseline. This is the case, for example, in calculating the cost of reduced mobility. To calculate these costs, the user must do some manual processing of MATHAIR outputs, i.e., subtract the quantities and costs of one MATHAIR output from those of another. ***

As with the Benefits Module, we discuss the Cost Module as if it performed the subtraction and calculated the total costs incurred by a control strategy.

MATHAIR OUTPUTS

The output of a MATHAIR simulation contains the following categories of information:

- Predicted emissions (tons/day) of CO, HC, NO_x, SO_x and Pb from automobiles, from all mobile sources, and from all stationary sources, respectively.
- Predicted ambient concentrations (ppm) of CO, NO_x, oxidants, and SO_x and of Pb ($\mu g/m^3$).
- Discounted costs and benefits for the strategy which has been simulated.

These outputs are generated for each year in the simulation horizon. A simulation output also contains the following information:

- Discounted present value of benefits and costs over the simulation horizon.
- Detailed intermediate output of the Transportation Module produced at the user's option. This

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* These costs are described by the economist's paradigm of consumers' surplus which is discussed in Appendix E.

** The RAND model [Goeller, B.F. et al, San Diego Clean Air Project, The RAND Corporation, R-1362-SD, (December 1973) and Mikolowsky, W.T. et al, The Regional Impacts of Near-Term Transportation Altertives: A Case Study of Los Angeles, The RAND Corporation, R-1524-SCAG (June 1974)] caclulates the number of foregone trips, but it does not associate a dollar value with them. Nor does it analyze enhanced mobility (i.e., induced trips).

***The calculations are described in Appendix E.

output includes the number of passenger trips, passenger miles, and vehicle miles for each type of trip as well as mode-split and trip frequency probabilities.

The benefit-cost framework of MATHAIR provides a single common denominator for all outcomes: dollars. In such a framework, the results of a strategy simulation can be represented by the dollar value of all of the costs involved and the dollar value of the benefits due to damage reduction. Net benefits can be calculated as one criterion for analyzing strategies. The marginal benefits and marginal costs of going from one strategy to a stricter one, can also be calculated. *

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* The RAND case study of Los Angeles [Mikolowsky, W. T. et al, The Regional Impacts of Near-Term Transportation Alternatives: A Case Study of Los Angeles, The RAND Corporation, R-1524-SCAG (June 1974)], for example, reports a vector of impacts for each strategy analyzed in the study. While such outputs are of course useful, the dollar common denominator has the advantage of providing the decision-maker with a simple strategy characterization. This is especially important when a large number of strategies are being compared.

SECTION VI

APPLICATION OF THE MODEL TO FOUR URBAN REGIONS

DESCRIPTION OF THE STUDY REGIONS AND DATA REQUIREMENTS

Description of the Study Regions

In order to test MATHAIR we have prepared input data for the urban regions containing the cities of Los Angeles, New York, Washington, D. C., and Chicago. These four cities represent a spectrum of the air pollution problems facing urban areas in the United States.

In each case we selected a study region that was larger than the city or the SMSA so that we could simulate travel within the urban area. The particular region boundaries were generally selected because pollutant emission and concentration data were available for those boundaries. Maps of the study regions are shown in Figures 3 through 6. In all cases we have divided the area into two parts which, for convenience, we call the center and the suburbs.

Data Needs

Six categories of data, corresponding to the six MATHAIR modules, are required for a MATHAIR simulation. The data that were used to test the model are presented in Appendix F. The six modules are listed below:

- Automobile Stock Module
- Transportation Module
- Emissions Module
- Air Quality Module
- Benefits Module
- Cost Module

In a number of cases, more recent data are now available than the data that were used to test the model. This is because work on this study began late in 1974. If additional MATHAIR simulations are run for the study regions, the data used as input to the parameter estimations and to the model should be updated.

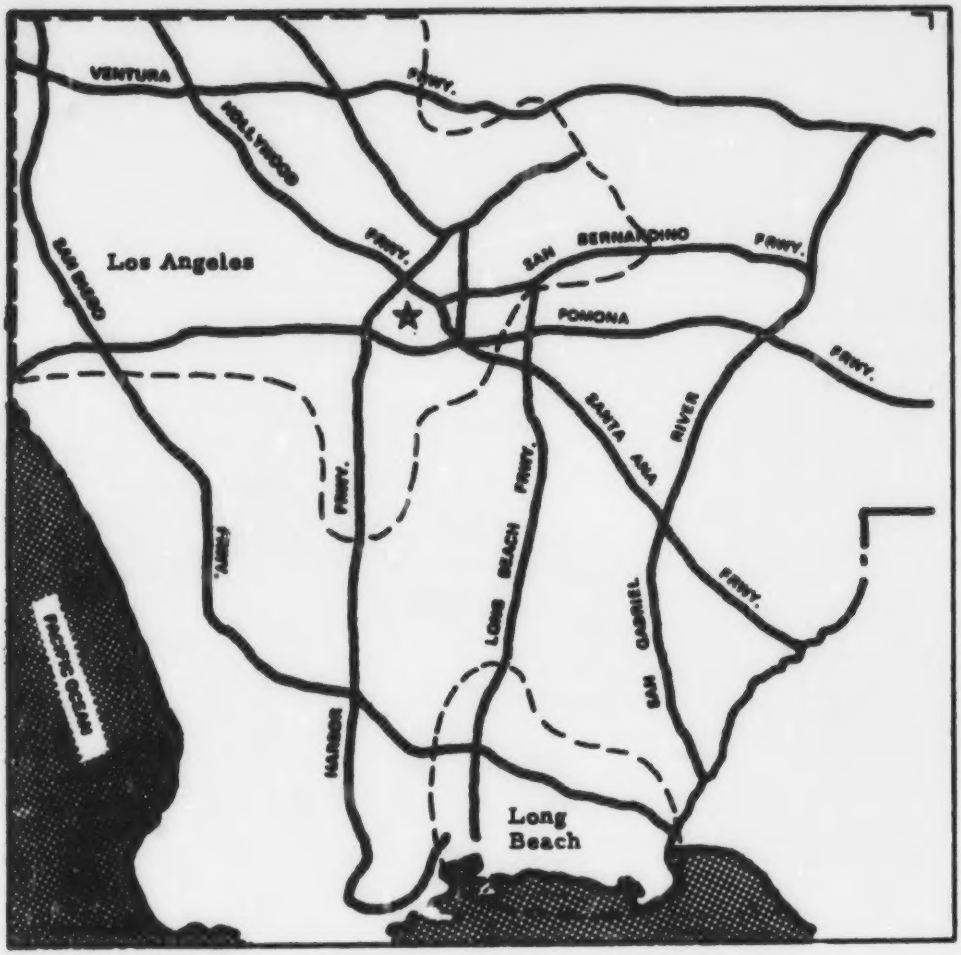

Figure 3. Los Angeles study region.

Source: Prediction of the Effects of Transportation Controls on Air Quality in Major Metropolitan Areas, U.S. Environmental Protection Agency, APTD-1363, November 1972, pp. 3-6.

Note: The entire area shown is the study region. The cities proper of Los Angeles and Long Beach, approximately enclosed in dashed lines, are the region's "center" for purposes of the Transportation Module.

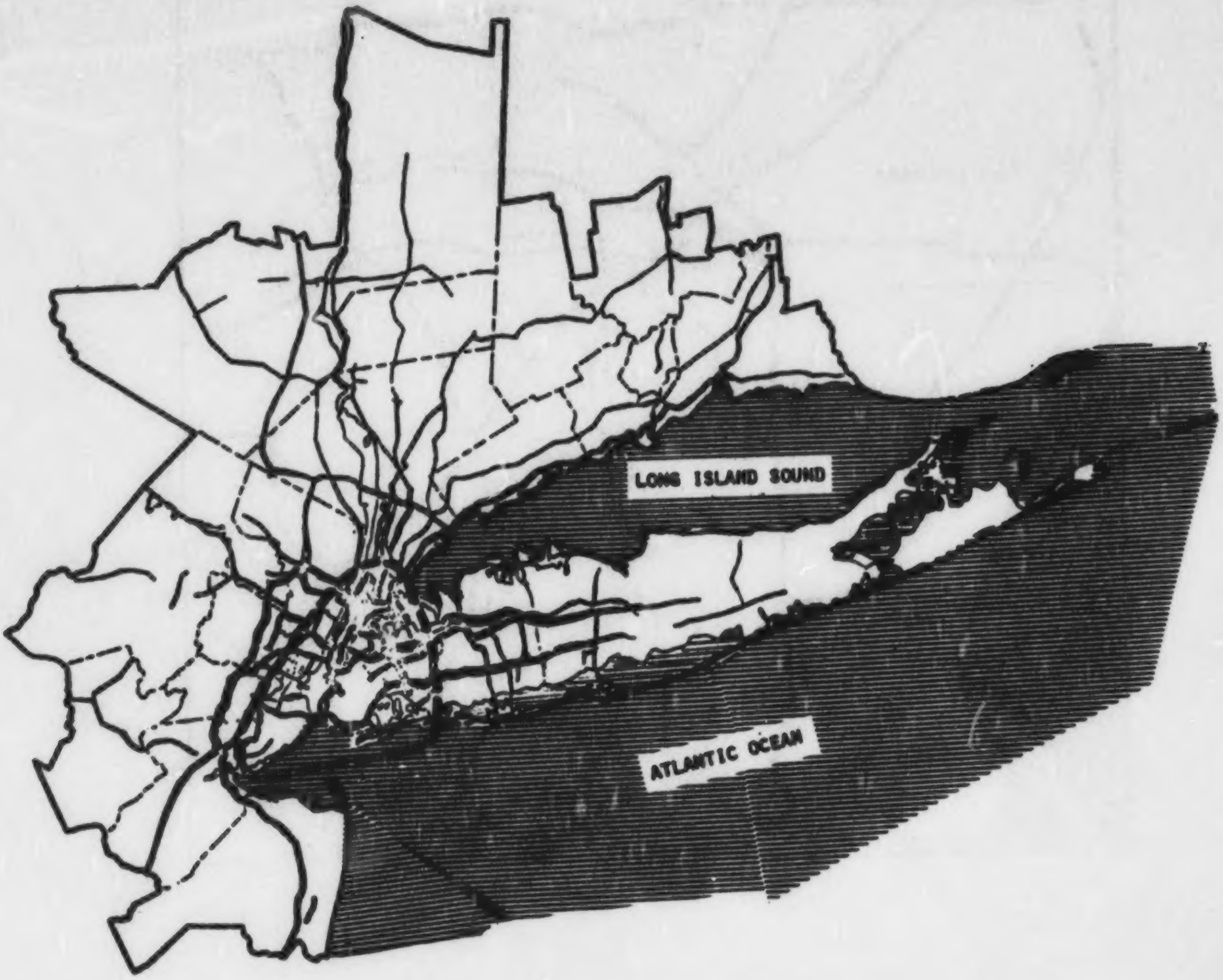

Figure 4. The Tri-State study region (New York, New Jersey, Connecticut).

Source: Vehicle Miles of Travel on Major Roadways: 1970, Tri-State Regional Planning Commission, November 1973, p. 2.

Note: The entire area shown is the study region. New York City, approximately enclosed in dashed lines, is the regions's "center" for purposes of the Transportation Module.

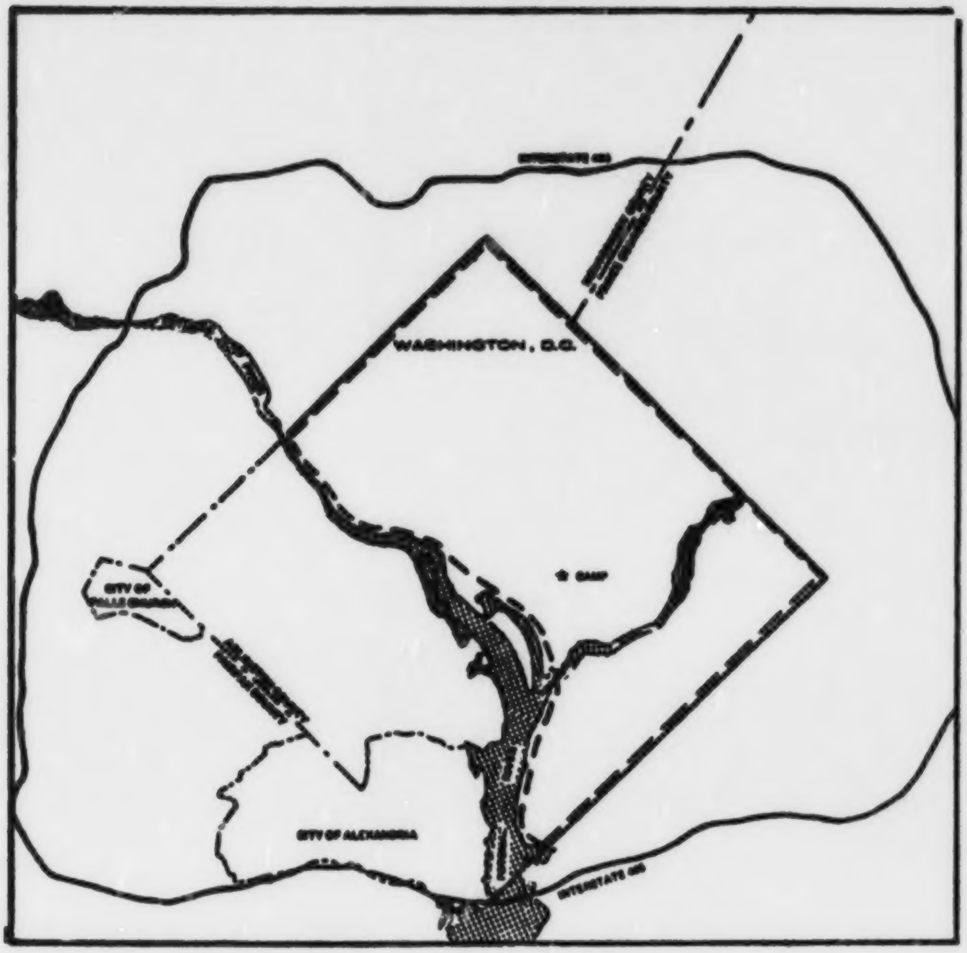

Figure 5. Washington, D.C., study region.

Source: Prediction of the Effects of Transportation Controls on Air Quality in Major Metropolitan Areas, U.S. Environmental Protection Agency, APTD-1363, November 1972, pp. 4-5.

Note: The entire area shown is the study region. The District of Columbia, enclosed in dashed lines, is the region's "center" for purposes of the Transportation Module.

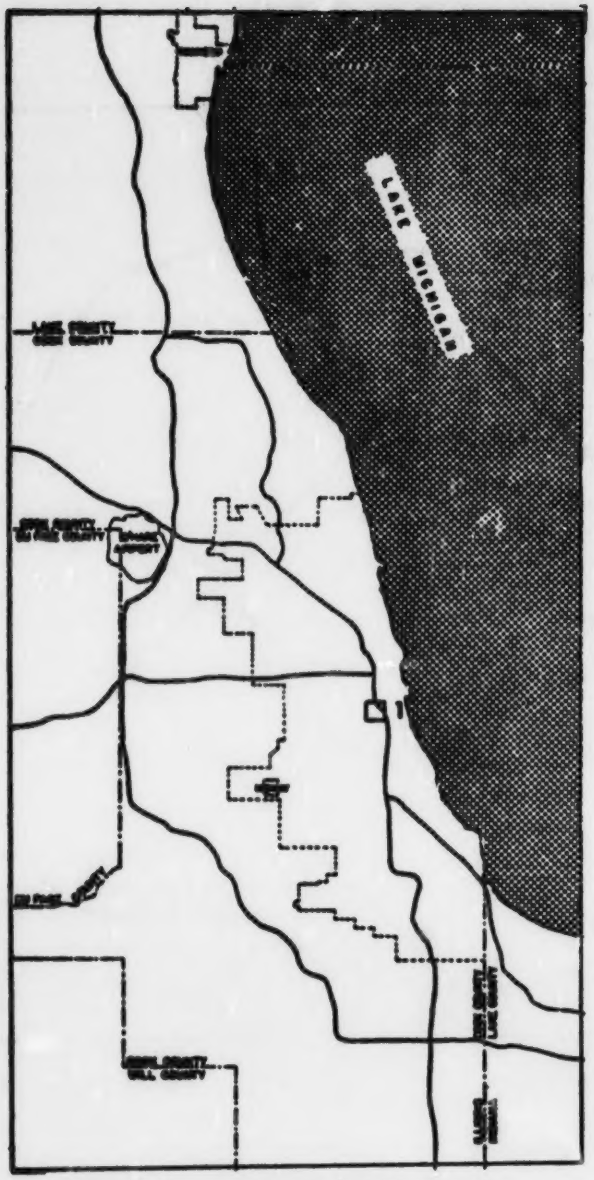

Figure 6. Chicago Study Region

Source: Prediction of the Effects of Transportation Controls on Air Quality in Major Metropolitan Areas, U.S. Environmental Protection Agency, APTD-1363, November 1972, pp. 3-7.

Note: The entire area shown is the study region. The city proper of Chicago, approximately enclosed in dashed lines, is the region's "center" for purposes of the Transportation Module.

In many cases the data needed as input to MATHAIR were available for the center only, for a metropolitan area of different boundaries than our study area (usually the SMSA), or could not be located at all. In these cases, we estimated the corresponding data for the study area.

Transportation Module--

Estimating a disaggregate behavioral demand model like our Transportation Module requires survey-type information about travel alternatives and decisions. It was not possible within the scope of this project for us to estimate equations for the four study regions.

The alternative we adopted was to use parameters estimated for Pittsburgh by other investigators.* We recalibrated the constant terms so that the Transportation Module's base year predictions for the study regions would fit observed data. The nature of the model offers some justification for the method we adopted since behavior of individuals faced with the same price and service characteristics of transportation alternatives can be assumed to be relatively independent of where the individual lives.

We undertook a validation of some of the output series of the transportation model against independent data series. The two series are generally acceptably close. Comparisons are presented in Appendix G.

Benefits Module--

The MATHAIR Benefits Module requires for each study region base year air quality measurements for each pollutant and the dollar value of each damage category by pollutant for the same base year. These data are used to calibrate the damage functions.

To our knowledge, estimates of the dollar value of pollution damage have been made only on a nationwide basis, and independent estimates are not in close agreement. Therefore, two problems had to be faced:

- select nationwide damage estimates, and
- disaggregate these estimates into damage estimates for specified urban regions.

The national pollution damage estimates used to test the model are the estimates of Barrett and Waddell, extended by Babcock and Nagda.**

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* A Disaggregated Behavioral Model of Urban Travel Demand, Charles River Associates (March 1972).

** All reported in Justus, C. G., J. R. Williams, and J. D. Clement, Economic Costs of Air Pollution Damage, STAR, Inc. (May 1973). The 1971 Barrett and Waddell estimates (using 1968 data) were extended by Babcock and Nagda in a 1973 study to include the effects on health and property of the mobile source pollutants.

Considerably lower estimates were made by Justus et al. * We have used these lower estimates in one of the scenarios simulated with MATHAIR in order to test the sensitivity of the model.

The methodology we have used for disaggregating national damage estimates to urban area estimates of damage by pollutant and damage category was developed by Justus et al. ** They calculated a "multiplier" for each of 65 SMSA's for five pollutants and seven damage effects. The product of the multiplier and the national loss estimate for all damage due to air pollution, is an estimate of the loss in one SMSA for one category of damage by one pollutant. The multipliers are determined by three factors:

- a severity factor (S_{pe}) which is a measure of the "toxicity" of pollutant p for damage effect e,
- an air quality exceedance factor (Amp) which measures the extent to which the air quality standard for pollutant p was exceeded in $SMSA_m$ in the base year, and
- an exposure factor (E_{me}) which measures the level of exposure in $SMSA_m$ to possible damage from effect e.

Total damage is assumed to be exhaustively distributed among the 65 SMSA's. The multiplier for an SMSA is the product of the three factors, normalized so that the sum of the multipliers is 1.00.

For each of our study regions we used the Justus multipliers adjusted for the difference in boundaries between the SMSA's and our study regions.*** In the test runs we have made, only three damage categories are considered: health, vegetation, and materials. Other categories of damage, like noise and congestion, which are also affected by the control strategies are not considered because they are even more difficult to quantify. The omission of the damages associated with these categories means, other things being equal, that the damages (and the benefits) calculated by MATHAIR should be regarded as lower bounds.

ESTIMATES OF AIR QUALITY AND MONETARY VALUE OF DAMAGES ASSUMING NO CONTROLS

We now report MATHAIR forecasts of air quality and dollar value of damages in the four study regions for the period 1975-1984 assuming no air pollution controls.

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* Ibid.

** Ibid.

*** The study region multiplier was calculated as the sum of the multipliers for all SMSA's included in the study region. Where an SMSA was partly included, judgmental decisions were made.

Air Quality

The air quality predictions are shown in Table 1. The scenario assumes no air pollution controls; that is, post-1967 automobiles in New York, Washington, D. C., and Chicago have 1967 vintage characteristics and post-1965 Los Angeles automobiles have 1965 characteristics.* The existing level of control of stationary sources is assumed.

Table 1 shows concentrations of CO, OX, and NO_x to be increasing over time. This increase is due solely to increased demand for trips as the population grows over the simulation horizon since stationary source emissions are assumed to remain constant. Concentrations of SO_x are also increasing, but very slowly, since mobile sources emit relatively small quantities of this pollutant. Lead concentrations are seen to be decreasing because we have assumed a gradual phasing out of lead from gasoline according to the schedule shown in Table F-24 of Appendix F.

The national ambient air quality standards are shown in Table 2 so that we can compare the MATHAIR outputs with the standards.** The standards for sulfur oxides are met in all four regions over the entire simulation horizon. This unrealistic prediction is due in part to the choice of a zero growth rate for stationary source emissions over the simulation horizon. In Washington, D.C., the standards for nitrogen oxides are also met. The standards for carbon monoxide and for oxidants are greatly exceeded in all areas.

Damages

MATHAIR forecasts of the dollar value of damages due to air pollution (1975 present value in 1973 dollars) for the four study regions are shown in Tables 3 through 6.

The loss due to sulfur oxides is shown to be zero for Los Angeles and for Washington, D. C. The explanation of this anomaly is that, in

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* In California, post-1965 automobiles were subject to controls. In the rest of the nation, post-1967 automobiles were the first to be controlled.

** The averaging times for measured pollutant concentrations used in calibrating rollback parameters for MATHAIR are shown below. The relevant standard is shown in the third column.

Pollutant	Averaging Time	Standard
CO	8 hour	9 ppm
NO_x	annual arithmetic mean	0.05 ppm
Oxidants	1 hour	0.08 ppm
SO_x	annual arithmetic mean	0.03 ppm
Pb	24 hour	-

TABLE 1. POLLUTANT CONCENTRATIONS FOR THE FOUR STUDY REGIONS ASSUMING NO AIR POLLUTION CONTROLS a/

Region	Year	Carbon Monoxide (CO)	Oxidants b/ OX1	OX2	OX3	Nitrogen Dioxides (NO_x)	Sulfur Oxides (SO_x)	Lead c/ (Pb)
Los Angeles	1975	54.7388	0.5096	0.4720	0.4483	0.0637	0.0158	31.97
	1976	55.7445	0.5169	0.4786	0.4544	0.0645	0.0158	22.02
	1977	56.7804	0.5246	0.4855	0.4607	0.0653	0.0158	13.88
	1978	57.8472	0.5326	0.4926	0.4672	0.0662	0.0159	10.13
	1979	58.9462	0.5409	0.5000	0.4740	0.0671	0.0159	7.14
	1980	60.0781	0.5495	0.5077	0.4811	0.0680	0.0159	4.93
	1981	61.2439	0.5585	0.5156	0.4883	0.0689	0.0159	3.39
	1982	62.4447	0.5677	0.5238	0.4958	0.0699	0.0160	2.28
	1983	63.6815	0.5773	0.5323	0.5036	0.0709	0.0160	1.54
	1984	64.9555	0.5872	0.5410	0.5116	0.0720	0.0161	1.02
New York	1975	30.6820	0.2558	0.2197	0.2140	0.0797	0.0109	6.69
	1976	30.8631	0.2569	0.2205	0.2147	0.0798	0.0109	4.71
	1977	31.0460	0.2580	0.2213	0.2154	0.0800	0.0109	3.05
	1978	31.2307	0.2592	0.2221	0.2161	0.0802	0.0109	2.31
	1979	31.4173	0.2604	0.2229	0.2169	0.0803	0.0109	1.70
	1980	31.6057	0.2617	0.2238	0.2176	0.0805	0.0109	1.20
	1981	31.7960	0.2630	0.2247	0.2184	0.0807	0.0109	0.82
	1982	31.9382	0.2643	0.2256	0.2192	0.0809	0.0109	0.55
	1983	32.1824	0.2657	0.2265	0.2200	0.0811	0.0109	0.36
	1984	32.3784	0.2671	0.2274	0.2208	0.0812	0.0109	0.24
Washington, D.C.	1975	42.5291	0.3497	0.3403	0.3348	0.0086	0.0155	21.04
	1976	43.1936	0.3557	0.3454	0.3393	0.0087	0.0155	14.60
	1977	43.8781	0.3618	0.3506	0.3440	0.0088	0.0155	9.42
	1978	44.5830	0.3681	0.3560	0.3488	0.0089	0.0155	7.18
	1979	45.3091	0.3746	0.3615	0.3538	0.0090	0.0155	5.30
	1980	46.0570	0.3812	0.3671	0.3588	0.0091	0.0155	3.80
	1981	46.8273	0.3879	0.3729	0.3639	0.0092	0.0155	2.61
	1982	47.6208	0.3946	0.3787	0.3692	0.0093	0.0156	1.74
	1983	48.4380	0.4015	0.3847	0.3745	0.0094	0.0156	1.18
	1984	49.2798	0.4086	0.3907	0.3800	0.0095	0.0156	0.79
Chicago	1975	34.2627	0.2464	0.2357	0.2246	0.0916	0.0217	9.54
	1976	34.7956	0.2491	0.2382	0.2268	0.0974	0.0218	6.75
	1977	35.3444	0.2519	0.2408	0.2291	0.0932	0.0218	4.42
	1978	35.9098	0.2549	0.2434	0.2315	0.0941	0.0218	3.39
	1979	36.4920	0.2579	0.2462	0.2340	0.0950	0.0218	2.51
	1980	37.0918	0.2610	0.2490	0.2365	0.0959	0.0218	1.80
	1981	37.7095	0.2642	0.2519	0.2392	0.0968	0.0218	1.24
	1982	38.3458	0.2675	0.2549	0.2419	0.0978	0.0218	0.84
	1983	39.0012	0.2710	0.2580	0.2446	0.0988	0.0218	0.57
	1984	39.6762	0.2745	0.2611	0.2475	0.0998	0.0218	0.38

Source: MATHAIR outputs.

a/ All units are reported in parts per million (ppm) except lead particulate which is reported in $\mu g/m^3$.

b/ Three alternative prediction equations were used for oxidant concentrations. . The equations are listed below:

$$OX1 = \alpha HC_S + \beta HC_M$$

$$OX2 = \gamma(HC_S + HC_M + NO_{xS} + NO_{xM})$$

$$OX3 = \delta(HC_S + HC_M)$$

where α, β, γ, and δ are calibration constants

HC = = hydrocarbons

NO_x = nitrogen oxides

Subscripts: S = Stationary source and M = mobile source

OX1 is the estimate used by the air quality module.

c/ Lead concentrations are seen to be decreasing because a schedule for phasing out the lead content gasoline was assumed.

TABLE 2. SUMMARY OF NATIONAL AMBIENT AIR QUALITY STANDARDS [a]

Pollutant	Averaging Time	Primary Standards	Secondary Standards
Particulate matter	Annual (Geometric mean)	75 $\mu g/m^3$	60 $\mu g/m^3$
	24-hour [b]	260 $\mu g/m^3$	150 $\mu g/m^3$
Sulfur oxides	Annual (Arithmetic mean)	80 $\mu g/m^3$ (0.03 ppm)	-
	24-hour [b]	365 $\mu g/m^3$ (0.14 ppm)	
	3-hour [b]	-	1300 $\mu g/m^3$ (0.5 ppm)
Carbon monoxide	8-hour [b]	10 mg/m^3 (9 ppm)	
	1-hour [b]	40 mg/m^3 (35 ppm)	(Same as primary)
Nitrogen dioxide	Annual (Arithmetic mean)	100 $\mu g/m^3$ (0.05 ppm)	(Same as primary)
Photochemical oxidants	1-hour [b]	160 $\mu g/m^3$ (0.08 ppm)	(Same as primary)

Source: Air Quality Data - 1972 Annual Statistics, U.S. Environmental Protection Agency (March 1974), p. iv.

[a] The air quality standards and a description of the reference methods were published on April 30, 1971, in 42 CFR 410, recodified to 40 CRF 50 on November 25, 1972.

[b] Not to be exceeded more than once per year.

the Justus study, these two cities are assigned air quality exceedance factors of zero for the base year for SO_x. Given the method of calculation, they will therefore always show a zero loss! These are obviously underestimates of the actual loss, and the allocation method furthermore forces the other cities to show compensating overestimated portions of the national estimates. While this is a serious problem with the procedure for disaggregating damages, it has a minimal effect on the benefit-cost analysis we will perform in Section VIII. *

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* Benefits are defined as the difference between damage loss under a given scenario and damage loss in the baseline case, and the difference forecasted in our test runs will always be zero. However, this is not a serious error. Since both quantities are in fact small positive numbers, the actual difference will be close to the predicted value of zero.

TABLE 3. DAMAGES DUE TO AIR POLLUTION IN LOS ANGELES ASSUMING NO AIR POLLUTION CONTROLS (1975 PRESENT VALUE IN MILLIONS OF 1973 DOLLARS)

Year	Damage Category	Carbon Monoxide (CO)	Oxidants (OX)	Nitrogen Oxides (NO_x)	Sulfur Oxides (SO_x)	Lead (Pb)
1975	Health	23.5	152.5	80.3	0.0	0.2
	Vegetation	0.0	35.9	6.9	0.0	0.0
	Materials	61.8	486.6	111.5	0.0	0.3
1976	Health	22.2	143.5	75.5	0.0	0.1
	Vegetation	0.0	33.3	6.4	0.0	0.0
	Materials	59.5	467.2	106.6	0.0	0.2
1977	Health	21.0	134.9	70.9	0.0	0.0
	Vegetation	0.0	30.9	5.9	0.0	0.0
	Materials	57.2	446.8	102.0	0.0	0.1
1978	Health	19.8	127.1	66.6	0.0	0.0
	Vegetation	0.0	28.6	5.5	0.0	0.0
	Materials	55.0	428.6	97.7	0.0	0.0
1979	Health	18.7	119.7	62.6	0.0	0.0
	Vegetation	0.0	26.6	5.1	0.0	0.0
	Materials	53.0	411.1	93.5	0.0	0.0
1980	Health	17.7	112.8	58.8	0.0	0.0
	Vegetation	0.0	24.8	4.6	0.0	0.0
	Materials	51.0	394.5	89.5	0.0	0.0
1981	Health	16.7	106.4	55.4	0.0	0.0
	Vegetation	0.0	22.9	4.3	0.0	0.0
	Materials	49.1	378.7	85.7	0.0	0.0
1982	Health	15.8	100.2	52.0	0.0	0.0
	Vegetation	0.0	21.3	4.0	0.0	0.0
	Materials	47.3	363.6	82.1	0.0	0.0
1983	Health	15.0	94.5	48.9	0.0	0.0
	Vegetation	0.0	19.9	3.8	0.0	0.0
	Materials	45.6	349.2	78.6	0.0	0.0
1984	Health	14.7	89.1	46.0	0.0	0.0
	Vegetation	0.0	18.5	3.4	0.0	0.0
	Materials	43.9	335.5	75.4	0.0	0.0

Source: MATHAIR outputs.

TABLE 4. DAMAGES DUE TO AIR POLLUTION IN NEW YORK ASSUMING NO AIR POLLUTION CONTROLS (1975 PRESENT VALUE IN MILLIONS OF 1973 DOLLARS)

Year	Damage Category	Carbon Monoxide (CO)	Oxidants (OX)	Nitrogen Oxides (NO_x)	Sulfur Oxides (SO_x)	Lead (Pb)
1975	Health	2.5	21.3	15.6	204.4	0.2
	Vegetation	0.0	0.8	1.1	32.8	0.0
	Materials	87.6	570.2	364.2	2386.6	5.7
1976	Health	2.3	19.7	14.4	188.3	0.1
	Vegetation	0.0	0.8	1.1	30.2	0.0
	Materials	82.6	537.2	342.5	2240.2	3.8
1977	Health	2.2	18.2	13.2	173.4	0.0
	Vegetation	0.0	0.6	1.0	27.7	0.0
	Materials	78.0	506.2	322.0	2102.3	2.3
1978	Health	1.9	16.9	12.3	159.7	0.0
	Vegetation	0.0	0.6	0.9	25.5	0.0
	Materials	73.6	477.1	302.8	1972.0	1.6
1979	Health	1.8	15.6	11.3	147.1	0.0
	Vegetation	0.0	0.5	0.8	23.5	0.0
	Materials	69.5	449.8	284.7	1850.3	1.1
1980	Health	1.7	14.4	10.4	135.5	0.0
	Vegetation	0.0	0.5	0.8	21.5	0.0
	Materials	65.5	424.0	267.6	1736.1	0.8
1981	Health	1.5	13.4	9.6	124.8	0.0
	Vegetation	0.0	0.4	0.6	19.82	0.0
	Materials	61.8	399.8	251.6	1629.5	0.4
1982	Health	1.4	12.4	8.9	114.9	0.0
	Vegetation	0.0	0.4	0.6	18.2	0.0
	Materials	58.4	377.0	236.6	1529.3	0.3
1983	Health	1.3	11.4	8.2	105.9	0.0
	Vegetation	0.0	0.4	0.5	16.7	0.0
	Materials	55.1	355.5	222.5	1434.6	0.2
1984	Health	1.2	10.6	7.5	97.6	0.0
	Vegetation	0.0	0.3	0.5	15.4	0.0
	Materials	52.0	335.3	209.2	1346.3	0.1

Source: MATHAIR outputs.

TABLE 5. DAMAGES DUE TO AIR POLLUTION IN WASHINGTON, D.C. ASSUMING NO AIR POLLUTION CONTROLS (1975 PRESENT VALUE IN MILLIONS OF 1973 DOLLARS)

Year	Damage Category	Carbon Monoxide (CO)	Oxidants (OX)	Nitrogen Oxides (NO_x)	Sulfur Oxides (SO_x)	Lead (Pb)
1975	Health	0.0	1.7	0.4	0.0	0.0
	Vegetation	0.0	1.0	0.3	0.0	0.0
	Materials	23.8	91.2	10.4	0.0	0.4
1976	Health	0.5	1.6	0.4	0.0	0.0
	Vegetation	0.0	1.0	0.3	0.0	0.0
	Materials	23.0	88.3	10.0	0.0	0.2
1977	Health	0.4	1.5	0.4	0.0	0.0
	Vegetation	0.0	0.9	0.2	0.0	0.0
	Materials	22.3	85.5	9.6	0.0	0.1
1978	Health	0.4	1.4	0.4	0.0	0.0
	Vegetation	0.0	0.9	0.2	0.0	0.0
	Materials	21.5	82.8	9.3	0.0	0.1
1979	Health	0.4	1.4	0.3	0.0	0.0
	Vegetation	0.0	0.8	0.2	0.0	0.0
	Materials	20.8	80.2	8.9	0.0	0.0
1980	Health	0.4	1.3	0.3	0.0	0.0
	Vegetation	0.0	0.8	0.2	0.0	0.0
	Materials	20.1	77.7	8.6	0.0	0.0
1981	Health	0.3	1.2	0.3	0.0	0.0
	Vegetation	0.0	0.6	0.2	0.0	0.0
	Materials	19.4	75.2	8.3	0.0	0.0
1982	Health	0.3	1.2	0.3	0.0	0.0
	Vegetation	0.0	0.6	0.2	0.0	0.0
	Materials	18.8	72.8	8.0	0.0	0.0
1983	Health	0.3	1.1	0.3	0.0	0.0
	Vegetation	0.0	0.5	0.1	0.0	0.0
	Materials	18.3	70.5	7.6	0.0	0.0
1984	Health	0.3	1.0	0.2	0.0	0.0
	Vegetation	0.0	0.5	0.1	0.0	0.0
	Materials	17.7	68.4	7.3	0.0	0.0

Source: MATHAIR outputs.

TABLE 6. DAMAGES DUE TO AIR POLLUTION IN CHICAGO ASSUMING NO AIR POLLUTION CONTROLS (1975 PRESENT VALUE IN MILLIONS OF 1973 DOLLARS)

Year	Damage Category	Carbon Monoxide (CO)	Oxidants (OX)	Nitrogen Oxides (SO_x)	Sulfur Oxides (SO_x)	Lead (Pb)
1975	Health	1.2	16.6	46.2	139.8	0.0
	Vegetation	0.0	3.4	10.2	83.1	0.0
	Materials	24.3	442.6	531.1	1034.5	0.3
1976	Health	1.2	15.5	42.9	128.8	0.0
	Vegetation	0.0	3.1	9.4	76.0	0.0
	Materials	23.4	421.9	505.1	975.5	0.2
1977	Health	1.1	14.4	39.8	118.7	0.0
	Vegetation	0.0	2.9	8.7	69.5	0.0
	Materials	22.4	402.3	480.6	920.1	0.1
1978	Health	1.0	13.5	37.0	109.3	0.0
	Vegetation	0.0	2.7	8.0	63.5	0.0
	Materials	20.9	383.6	457.2	867.7	0.0
1979	Health	1.0	12.5	34.5	100.7	0.0
	Vegetation	0.0	2.5	7.4	58.1	0.0
	Materials	20.5	365.9	435.1	818.4	0.0
1980	Health	0.9	11.6	32.0	92.7	0.0
	Vegetation	0.0	2.3	6.8	53.1	0.0
	Materials	19.7	354.5	414.1	771.9	0.0
1981	Health	0.9	10.9	29.8	85.5	0.0
	Vegetation	0.0	2.2	6.2	48.6	0.0
	Materials	18.3	333.2	396.3	728.1	0.0
1982	Health	0.8	10.1	27.7	78.7	0.0
	Vegetation	0.0	1.9	5.8	44.3	0.0
	Materials	18.1	318.0	375.3	686.7	0.0
1983	Health	0.8	9.5	25.7	72.6	0.0
	Vegetation	0.0	1.8	5.4	40.5	0.0
	Materials	17.3	303.6	357.5	647.7	0.0
1984	Health	0.6	8.8	24.0	66.9	0.0
	Vegetation	0.0	1.7	5.0	37.0	0.0
	Materials	16.6	289.9	340.5	610.9	0.0

Source: MATHAIR outputs.

SECTION VII

CHANGES IN AIR QUALITY USING ALTERNATIVE AIR POLLUTION CONTROL STRATEGIES

In this section we use the MATHAIR model to calculate the impact of alternative pollution control strategies on air quality. We begin by describing how the particular strategies were chosen and then examine their possible impact on air quality in Los Angeles, New York, Washington, D. C., and Chicago.

AIR POLLUTION CONTROL STRATEGIES CONSIDERED

The Principle of Strategy Selection

The basic principle for selecting strategies was to develop air pollution control strategies involving progressively more stringent controls. Starting with a zero strategy, S0, involving no controls, more stringent control is achieved through either additional control measures or stricter application of existing controls. Strategies ordered by amount and degree of control are assumed to result in progressively improved air quality. While there is no single physical unit for measuring air quality (or pollution reduction) since several pollutants are involved, the improvements in air quality are measured in MATHAIR by the estimated dollar value of damage reduction.

The strategies considered here consist of combinations of measures for controlling emissions of carbon monoxide, hydrocarbons, and nitrogen oxides. We have not included measures for controlling emissions of lead or sulfur oxides in the strategies. Neither Federal nor State transportation control plans have required controls of these pollutants. Furthermore, mobile sources account for less than 5 percent of sulfur oxide emissions. Control measures for these pollutants could, however, be simulated with MATHAIR.

The five types of control measures of which our strategies are composed are the following:

- hardware devices for new automobiles
- retrofit devices for existing automobiles

- inspection and maintenance (I/M) for new and existing automobiles
- transportation controls for reducing the use of the automobile
- hardware devices for stationary sources of pollution

Figure 7 shows an example, in matrix form, of four increasingly stringent strategies and the zero control strategy. The columns of the matrix correspond to the five types of control measures and the rows to the five strategies.

	Control Devices For New Automobiles	Retrofit Control Devices	Inspection and Maintenance	Transportation Controls	Stationary Source Controls
Strategy 0 (S0)	-	-	-	-	-
Strategy 1 (S1)	low	-	-	-	low
Strategy 2 (S2)	moderate	-	-	-	moderate
Strategy 3 (S3)	moderate	-	for all automobiles	-	moderate
Strategy 4 (S4)	high	required	for all automobiles	required	moderate

Matrix columns correspond to control measures and rows correspond to strategies. Entries describe the level of control.

Figure 7. Example of five increasingly stringent air pollution control strategies.

The first row of the matrix corresponds to S0. Since zero controls are required, there are no entries in this row. The first strategy, S1, involves a low level of control for each of two types of measures. These might take the form of minor hardware adjustments on all new automobiles built after a certain date and the installation of an assortment of suitable control devices on various types of stationary sources of pollution. The low level of control in the latter case might be reflected by installing controls on only a small percentage of each type of plant. *

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* It is convenient to designate an individual unit of stationary source pollution as a "plant." This term must be understood in a very general sense. Airplane ground operations, for example, are a "stationary" source of pollution and a plant, in this case, is a single airport.

The second strategy, S2, requires an increased level of control for the same two measures. A moderate level of control through devices for new automobiles might take the form of more extensive adjustment, including additional devices, and an earlier starting date. In the case of stationary source controls, the percentage of plants fitted with control devices could be increased.

The next row of the matrix in Figure 7 corresponds to the third strategy, S3. S3 adds I/M for all automobiles to the requirements of S2.

The final strategy, S4, requires two new kinds of control and increases the severity of a third measure. A higher level of control through new automobile devices could be achieved by requiring additional devices not specified in the preceding strategy. In addition, certain retrofit control devices are required and a reduction in the use of automobiles is achieved through transportation controls.

Control Measures for Mobile Sources

Hardware Devices for New Automobiles--

Automobile manufacturers have been required to comply with new automobile emission standards since 1967 (California since 1965). Emission reductions have been achieved through engine adjustments and installation of pollution control devices. The zero control strategy, S0, assumes that these adjustments and installation of devices were not made, and that automobiles built after 1967 (1965 in California) have 1967 (1965) model emission characteristics. *

We will consider the following three measures for inclusion in our control strategies:

- All automobiles built before 1974 are assumed to meet the applicable Federal (or California) new automobile interim emission standards (shown in Table 7) and 1974 standards are required for 1975 and later model automobiles.
- All new automobiles built before 1975 are assumed to meet the applicable Federal (or California) new automobile interim emission standards, and the 1975 interim standards are required for 1976 and later model new automobiles.

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* In the case of the stationary sources of pollution, however, S0 assumes the existing level of control.

TABLE 7. FEDERAL EXHAUST EMISSION STANDARDS AND CONTROL LEVELS FOR LIGHT-DUTY VEHICLES (UNDER 6,000 LB. GROSS VEHICLE WEIGHT)

Model Year of Implementation	Standard	Hydrocarbons		Carbon Monoxide		Nitrogen Oxides	
		Gram/Mile	Reduction, percent	Gram/Mile	Reduction, percent	Gram/Mile	Reduction, percent
Pre-1968	Uncontrolled vehicles	8.7	--	87	--	5.5	--
1973/74	1973/74 Federal Standards	3.0	66	28	67	3.1	44
1975	1975 National Interim Standards(b)	1.5	83	15	83	3.1	44
1976	1975 Statutory Clean Air Standards and 1976 Interim Standards	0.41	95	3.4	96	2.0	64
1977	1976 Statutory Clean Air Standards	0.41	95	3.4	96	0.4	93

(a) Emission levels are measured on the 1975 Constant Volume Sample, Cold/Hot Weighing Mass Test Procedures (CVS-CH).

(b) Interim California Standards: 0.9 gram/mile hydrocarbons, 9.0 gram/mile carbon monoxide, and 2.0 gram/mile nitrogen oxides.

Source: "The Cost of Clean Air", Annual Report of the Administrator Environmental Protection Agency to the Congress of the United States (April 1974).

- All new automobiles built before 1975 are assumed to meet the applicable Federal (or California) new automobile interim emission standards, and 1975 interim standards are required for 1976 and later model new automobiles. In addition 1978 standards for carbon monoxide, hydrocarbons, and nitrogen oxides must be attained by all post-1977 automobiles (as with a three-way catalytic convertor).

Retrofit Devices for In-Use Automobiles--

Certain kinds of pollution control hardware devices can be retrofitted onto existing automobiles. Three devices, which are likely to be widely used for this purpose, are listed below with brief descriptions of their mode of control:

- Vacuum Spark Advance Disconnect (VSAD) -- The idle air-fuel mixture is made leaner, idle speed is increased and vacuum timing advance is made inoperative during normal engine operation. VSAD can be installed in pre-1968 automobiles.
- Air Bleed to Intake Manifold -- The air-fuel ratio is increased by means of an air valve to the intake system. This device is useful for pre-1972 automobiles.
- Oxidizing Catalytic Convertor -- A catalytic convertor is installed in the exhaust system of some pre-1974 automobiles to oxidize CO and HC.

I/M for New and In-Use Automobiles--

I/M programs are intended for the diagnosis and subsequent correction of excessive emissions. It is generally believed that a transportation program requiring hardware control devices on new and/or in-use automobiles should be accompanied by mandatory I/M to get full advantage of the control device. I/M is also useful as a stand-alone measure. *

Measures for Reducing Automobile Travel--

Automobile travel can be reduced through directly restraining the use of automobiles and through improving the level of service of mass transportation. Both types of measures encourage a shift from automobile

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* A maintenance program can improve the gasoline consumption characteristics of automobiles. We will have more to say about this subject in Section VIII.

travel to mass transportation.

Restraints on the use of automobiles include physical barriers, like exclusion from certain roads or effective gasoline rationing, and increased costs due to taxes or fees on gasoline, parking, or road use. Besides improving air quality, these measures may have other effects like reducing noise, congestion, and energy consumption.

The level of service of mass transportation (bus and rapid transit) can be improved by shortening headways, * extending areas covered, reducing fares, and in, in the case of buses, establishing exclusive bus lanes.

For the purpose of specifying strategies, we will be interested in the direct effects of such measures on travel time and out-of-pocket costs. From this view, the above measures can be restated as follows:

- increase in per/trip or per/mile cost of automobile travel
- increase in automobile transit time
- decrease in fares for mass transportation
- decrease in waiting or transit times for mass transportation

Control Measures for Stationary Sources of Air Pollution

The major stationary source pollutants are sulfur oxides and particulate matter. However, it is possible to identify a number of stationary sources of the mobile source pollutants, CO, HC, and NO_x, and to specify suitable controls. Examples of control measures would include the following:

- Hydrocarbon emissions during gasoline distribution and marketing can be controlled by installing hardware devices to collect the vapors.
- Tank roof designs can incorporate controls for hydrocarbon emissions from petroleum storage tanks.
- Thermal or catalytic incineration can control industrial evaporation of hydrocarbons from industries like printing or surface coating.
- Aircraft ground operations emissions of carbon monoxide and hydrocarbons can be controlled by modifying the operating characteristics of the turbine or piston engine.

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* Headway is the scheduled time between two vehicles traveling the same route.

- Nitrogen dioxide emissions from coal-, oil-, and gas-fired utility boilers can be controlled by combustion modifications like water injection or low excess air.

Strategies Selected

Four increasingly stringent strategies, S1 through S4, using the control measures discussed earlier, are presented in Figure 8.

There are no entries in Figure 8 for the zero control strategy S0. The first strategy, S1, represents a modest level of control. S1 requires some new automobile control devices and stationary source controls on specified percentages of different types of plant. Control device emission reduction characteristics typically assume an otherwise uncontrolled source. * The percentages of installations to be controlled by the strategies were arrived at after making rough estimates of the existing levels of control of different types of plant.

The next two strategies, S2 and S3, can be considered moderate or "most likely" scenarios. S2 requires more of the same kinds of controls as S1. An additional new automobile device is required and a larger percent of stationary installations is controlled. The third strategy adds I/M for all automobiles to the requirements of S2.

We have specified three variants of S4, our most stringent strategy. All three require a more effective device on post-1977 automobiles than does S3 as well as adding retrofit devices for the in-use automobile stock and transportation controls. Transportation controls for reducing the use of the automobile may take the form of increasing the cost of using the automobile or decreasing the cost of mass transportation. It is generally believed that the latter type of control must be accompanied by some form of automobile use restraint in order to be effective in reducing the use of automobile. To test this hypothesis, we have devised three transportation control measures (whose impacts are compared in Section IX). Strategy S4.1 increases the cost per mile of automobile travel by half: this measure might, for example, be implemented by increasing the gasoline tax. S4.2 decreases bus fare by one-third. Finally, S4.3 combines both of these transportation control measures.

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* One example is the case of incremental improvements: Combustion modifications on an uncontrolled utility boiler will be more effective than the same adjustments to a boiler that has already undergone other combustion modifications. Another type of example is the case where control devices are already in place. If 50 percent of existing petroleum storage tanks are equipped with roof designs that limit hydrocarbon evaporation, only the remaining 50 percent is subject to this type of control.

	New Automobile Control Devices	Retrofit Control Devices	Inspection and Maintenance (I/M)	Transportation Controls	Stationary Source Controls	
					Source	% of Installations Controlled
S0	—	—	—	—	—	—
S1	• 1968-1974 automobiles meet federal (or state) emission standards (Los Angeles: 1966-1974) • 100% of post-1974 automobiles have 1974 model characteristics	—	—	—	• Electricity generation by gas • Electricity generation by oil • Petroleum industry • Industrial HC evaporation • Gasoline handling • Aircraft	32 18 25 25 25 25
S2	1968-1974 automobiles meet federal (or state) emissions standards (Los Angeles: 1966-1974) 100% of post-1974 automobiles have 1974 model characteristics • 50% of post-1974 automobiles equipped with catalytic convertor (Los Angeles: 90%)	—	—	—	• Electricity generation by gas • Electricity generation by oil • Petroleum industry • Industrial HC evaporation • Gasoline handling Aircraft	64 36 50 50 50 50
S3	1968-1974 automobiles meet federal (of state) emissions standards (Los Angeles: 1966-1974) 100% of post-1974 automobiles have 1974 model characteristics 50% of post-1974 automobiles equipped with catalytic convertor (Los Angeles: 90%)	—	• I/M for 100% of all new and in-use automobiles	—	Electricity generation by gas Electricity generation by oil Petroleum industry Industrial HC evaporation Gasoline handling Aircraft	64 36 50 50 50 50
S4	1968-1974 automobiles meet federal (or state) emissions standards (Los Angeles: 1966-1974) 100% of post-1974 automobiles have 1974 model characteristics 50% of 1975-1977 automobiles equipped with catalytic convertor (Los Angeles: 90%) • 3-way catalytic convertor on 90% of post-1977 automobiles	• VSAD on 100% of 1955-1965 automobiles • Airbleed on 50% of 1955-1971 automobiles • Catalytic convertor on 20% of 1968-1974 automobiles	I/M for 100% of all new and in-use automobiles	• Average auto cost per mile increased by one-half (Strategy S4.1) or • Busfare decreased one-third (Strategy S4.2) or • Average auto cost per mile increased by one-half and busfare decreased one-third (Strategy S4.3)	Electricity generation by gas Electricity generation by oil Petroleum industry Industrial HC evaporation Gasoline handling Aircraft	64 36 50 50 50 50

Figure 8. Strategies selected for simulation with MATHAIR.

EFFECTS OF CONTROL STRATEGIES ON AIR QUALITY FOR THE FOUR STUDY REGIONS

In the second part of this section we report the MATHAIR air quality predictions for the period 1975 to 1984 in the four urban areas for the pollution control strategies discussed earlier. Results for strategy S2 are not presented for reasons which will be discussed in Section VIII. Futhermore, results for only the first variant of S4 (S4. 1) are presented in this section.

Air quality outcomes for the zero control strategy, S0 , are shown in Table 8 and discussed in Section VI. Tables 8 through 11 show the air quality predictions for the four study regions for strategies S1, S3, and S4. 1 and also indicate the air quality standards for each pollutant.

Air quality predictions for Los Angeles are shown in Table 8.

TABLE 8 AIR QUALITY IN LOS ANGELES FOR THREE SELECTED STRATEGIES (PPM)

Strategy	Year	Carbon Monoxide (CO)	Oxidants (OX)			Nitrogen Oxides (NO_x)	Sulfur Oxides (SO_x)
			OX1	OX2	OX3		
Strategy 1	1975	27. 0579	0. 2661	0. 2989	0. 3113	0. 0588	0. 0158
	1976	27. 0336	0. 2537	0. 2876	0. 3001	0. 0573	0. 0158
	1977	23. 4120	0. 2444	0. 2791	0. 2917	0. 0562	0. 0158
	1978	22. 2543	0. 2386	0. 2738	0. 2865	0. 0555	0. 0159
	1979	21. 5320	0. 2353	0. 2711	0. 2839	0. 0553	0. 0159
	1980	21. 0851	0. 2360	0. 2716	0. 2844	0. 0553	0. 0159
	1981	20. 8940	0. 2378	0. 2733	0. 2861	0. 0556	0. 0159
	1982	20. 8681	0. 2607	0. 2895	0. 3006	0. 0560	0. 0160
	1983	20. 9625	0. 2820	0. 3047	0. 3140	0. 0565	0. 0160
	1984	21. 1525	0. 3017	0. 3192	0. 3266	0. 0571	0. 0161
Strategy 3	1975	22. 2574	0. 2268	0. 2641	0. 2772	0. 0547	0. 0158
	1976	18. 7369	0. 2024	0. 2387	0. 2510	0. 0503	0. 0158
	1977	15. 5773	0. 1816	0. 2164	0. 2279	0. 0462	0. 0158
	1978	13. 0419	0. 1655	0. 1986	0. 2094	0. 0428	0. 0159
	1979	11. 0070	0. 1528	0. 1850	0. 1953	0. 0403	0. 0159
	1980	9. 4865	0. 1458	0. 1764	0. 1862	0. 0384	0. 0159
	1981	8. 4625	0. 1417	0. 1714	0. 1809	0. 0373	0. 0159
	1982	7. 7119	0. 1595	0. 1818	0. 1900	0. 0365	0. 0160
	1983	7. 2409	0. 1768	0. 1925	0. 1989	0. 0361	0. 0160
	1984	6. 9338	0. 1930	0. 2031	0. 2074	0. 0360	0. 0161
Strategy 4. 1	1975	13. 4732	0. 1814	0. 2212	0. 2337	0. 0486	0. 0156
	1976	11. 7851	0. 1651	0. 2043	0. 2160	0. 0454	0. 0156
	1977	10. 2726	0. 1533	0. 1895	0. 2005	0. 0423	0. 0157
	1978	8. 8677	0. 1426	0. 1740	0. 1889	0. 0383	0. 0157
	1979	7. 7150	0. 1341	0. 1616	0. 1705	0. 0350	0. 0157
	1980	6. 7976	0. 1294	0. 1529	0. 1608	0. 0323	0. 0158
	1981	6. 1389	0. 1264	0. 1468	0. 1539	0. 0308	0. 0158
	1982	5. 6250	0. 1404	0. 1528	0. 1578	0. 0287	0. 0158
	1983	5. 2746	0. 1536	0. 1593	0. 1618	0. 0275	0. 0158
	1984	5. 0362	0. 1661	0. 1662	0. 1659	0. 0268	0. 0159
Standards		9. 0	. 08			. 05	. 03

Source: MATHAIR output

One of the impacts of strategy S1 is a significant reduction in carbon monoxide (CO), and oxidant (OX) concentrations with respect to the zero control strategy outcome. Concentrations of the third major mobile source pollutant, nitrogen oxides (NO_x), are also reduced. Table 8 shows an initial decline in concentrations of these three pollutants over time as the controls are introduced. Eventually, all three levels begin to increase (starting in 1983 for CO, 1980 for OX, and 1980 or 1981 for NO_x). The increasing use of the automobile dominates further emission reductions, once the controls have had their principal impact. SO_x is not subject to controls and, therefore, concentrations are the same as they were in the case of the zero strategy, S0. The standards for CO, HC, and NO_x are not met even by 1984.

Concentrations of CO, HC, and NO_x are further reduced under strategy S3. The CO and NO_x controls are sufficiently effective in the later years of the simulation horizon that reduction in concentrations is monotonic. The oxidant levels, however, begin to increase in 1982. Under this scenario, the CO standard is met by 1981 and the NO_x standard by 1977.

All pollutant concentrations are further reduced under strategy S4. 1. The CO standard is met by 1978. The NO_x standard is satisfied for each simulation year. The oxidant standard cannot be met, and concentrations begin to increase after 1981. Even though there have been no direct controls of SO_x, concentrations are somewhat lower than in the case of the other strategies since the use of automobiles has been reduced.

Overall, controls in Los Angeles are effective in improving air quality. However, the MATHAIR simulation results confirm the well-known oxidant problem.

Predicted pollutant concentrations for New York are shown in Table 9. As in the case of Los Angeles, CO and OX concentrations are significantly reduced and NO_x concentrations are somewhat attenuated by the S1 scenario. Oxidant levels begin to increase after 1980 for the reason cited in the analysis of Los Angeles outcomes. The CO, HC, and NO_x standards are not satisfied in any simulation year.

Concentrations of CO, HC, and NO_x are somewhat further reduced by S3. The analysis of S1 outcomes holds equally for S3. With S4. 1 the CO standard is met in 1975 and the NO_x standard is satisfied by 1982. While the oxidant standard cannot be met even with our strictest control strategy, it is nearly achieved. SO_x concentrations are slightly reduced due to restricted use of the automobile. Overall, we can conclude that controls are effective in improving air quality in New York.

Table 10 shows predicted pollutant concentrations for Washington, D. C. As in the cases of Los Angeles and New York, CO and OX levels are significantly reduced by the first control strategy. However, CO and OX concentrations begin to increase in 1983 and 1980, respectively, and neither the CO nor the HC standard can be met. While NO_x concentra-

TABLE 9. AIR QUALITY IN NEW YORK FOR THREE SELECTED STRATEGIES (PPM)

Strategy	Year	Carbon Monoxide (CO)	Oxidants (OX)			Nitrogen Oxides (NO_x)	Sulfur Oxides (SO_x)
			OX1	OX2	OX3		
Strategy 1	1975	16.9442	0.1485	0.1569	0.1574	0.0742	0.0109
	1976	15.6198	0.1406	0.1513	0.1518	0.0730	0.0109
	1977	14.5587	0.1340	0.1468	0.1472	0.0719	0.0109
	1978	13.7236	0.1294	0.1433	0.1437	0.0710	0.0109
	1979	13.1359	0.1262	0.1409	0.1412	0.0702	0.0109
	1980	12.7420	0.1250	0.1397	0.1400	0.0697	0.0109
	1981	12.4871	0.1308	0.1425	0.1429	0.0694	0.0109
	1982	12.3279	0.1364	0.1453	0.1457	0.0693	0.0109
	1983	12.2420	0.1416	0.1479	0.1484	0.0692	0.0109
	1984	12.2074	0.1483	0.1515	0.1519	0.0692	0.0109
Strategy 3	1975	15.3224	0.1271	0.1396	0.1400	0.0685	0.0109
	1976	13.8792	0.1176	0.1331	0.1333	0.0672	0.0109
	1977	12.8021	0.1107	0.1281	0.1281	0.0660	0.0109
	1978	12.0563	0.1063	0.1247	0.1246	0.0649	0.0109
	1979	11.6207	0.1089	0.1226	0.1223	0.0641	0.0109
	1980	11.4196	0.1036	0.1218	0.1216	0.0635	0.0109
	1981	11.3675	0.1105	0.1251	0.1252	0.0632	0.0109
	1982	11.3933	0.1171	0.1284	0.1287	0.0630	0.0109
	1983	11.4561	0.1230	0.1314	0.1318	0.0629	0.0109
	1984	11.5382	0.1304	0.1353	0.1357	0.0628	0.0109
Strategy 4.1	1975	8.1096	0.0909	0.1084	0.1081	0.0572	0.0108
	1976	7.7558	0.0872	0.1058	0.1054	0.0567	0.0108
	1977	7.5471	0.0846	0.1039	0.1033	0.0561	0.0108
	1978	7.2366	0.0823	0.1010	0.1004	0.0545	0.0108
	1979	6.9804	0.0806	0.0986	0.0980	0.0531	0.0108
	1980	6.7555	0.0797	0.0967	0.0963	0.0518	0.0108
	1981	6.5498	0.0824	0.0971	0.0969	0.0507	0.0108
	1982	6.3495	0.0848	0.0975	0.0975	0.0499	0.0108
	1983	6.1497	0.0869	0.0978	0.0980	0.0491	0.0108
	1984	5.9684	0.0898	0.0988	0.0990	0.0486	0.0108
Standards		9.0	.08			.05	.03

Source: MATHAIR output

TABLE 10. AIR QUALITY IN WASHINGTON, D. C., FOR THREE SELECTED STRATEGIES (PPM)

Strategy	Year	Carbon Monoxide (CO)	Oxidants (OX)			Nitrogen Oxides (NO_x)	Sulfur Oxides (SO_x)
			OX1	OX2	OX3		
Strategy 1	1975	20.0693	0.1706	0.2159	0.2296	0.0083	0.0155
	1976	19.2152	0.1584	0.2053	0.2136	0.0081	0.0155
	1977	17.9463	0.1498	0.1974	0.2103	0.0079	0.0155
	1978	17.0237	0.1443	0.1922	0.2048	0.0078	0.0155
	1979	16.4456	0.1415	0.1893	0.2018	0.0077	0.0155
	1980	16.1495	0.1419	0.1891	0.2015	0.0077	0.0155
	1981	16.0240	0.1554	0.1983	0.2109	0.0077	0.0155
	1982	16.0151	0.1683	0.2073	0.2199	0.0077	0.0156
	1983	16.0956	0.1807	0.2162	0.2286	0.0078	0.0156
	1984	16.2396	0.1962	0.2274	0.2391	0.0078	0.0156
Strategy 3	1975	18.6065	0.1540	0.2022	0.2154	0.0081	0.0155
	1976	16.6259	0.1390	0.1894	0.2019	0.0079	0.0155
	1977	16.3071	0.1295	0.1806	0.1924	0.0077	0.0155
	1978	14.5138	0.2345	0.1755	0.1869	0.0075	0.0155
	1979	14.1748	0.1231	0.1733	0.1845	0.0074	0.0155
	1980	14.1822	0.1254	0.1742	0.1855	0.0074	0.0155
	1981	14.3904	0.1411	0.1846	0.1966	0.0074	0.0155
	1982	14.6975	0.1560	0.1949	0.2070	0.0074	0.0156
	1983	15.0212	0.1700	0.2047	0.2196	0.0074	0.0156
	1984	15.3611	0.1868	0.2166	0.2278	0.0075	0.0156
Strategy 4.1	1975	11.4460	0.1172	0.1667	0.1773	0.0072	0.0154
	1976	10.7654	0.1088	0.1594	0.1693	0.0071	0.0154
	1977	10.4634	0.1042	0.1547	0.1641	0.0070	0.0154
	1978	9.9176	0.0999	9.1463	0.1554	0.0065	0.0154
	1979	9.5247	0.0975	0.1396	0.1485	0.0061	0.0155
	1980	9.1663	0.0969	0.1348	0.1436	0.0057	0.0155
	1981	8.8652	0.1065	0.1402	0.1487	0.0054	0.0155
	1982	8.5180	0.1149	0.1402	0.1486	0.0052	0.0155
	1983	8.1266	9.1223	0.1426	0.1501	0.0050	0.0155
	1984	7.7333	0.1318	0.1469	0.1531	0.0048	0.0155
Standards		9.0	.08			.05	.03

Source: MATHAIR output

tions are slighly reduced from the levels predicted by MATHAIR for the zero control strategy, the standard for NO$_x$ is met even with no controls.

Concentrations of CO, HC, and NO$_x$ are somewhat further reduced by S3. The analysis of S1 outcomes holds equally for S3.

All concentration levels are further reduced by S4.1. CO concentrations decrease monotonically over time, and the standard can be met by 1981. SO$_x$ emissions decline slighly, as in the case of the other study areas, due to diminished automobile usage. The oxidant standard still cannot be met.

Overall, the controls are effective in improving air quality.

Finally, we turn to Table 11 which shows the MATHAIR predictions of pollutant concentrations in Chicago. As in the other study regions, S1 has the effect of significantly decreasing CO and OX concentrations and of slightly reducing the ambient level of NO$_x$. However, levels of these three pollutants begin to increase in 1983, 1981 and 1982 respectively. The standards cannot be met for any of these three pollutants.

TABLE 11. AIR QUALITY IN CHICAGO FOR THREE SELECTED STRATEGIES (PPM)

Strategy	Year	Carbon Monoxide (CO)	Oxidants (OX)			Nitrogen Oxides (NO$_x$)	Sulfur Oxides (SO$_x$)
			OX1	OX2	OX3		
Strategy 1	1975	18.3919	0.1502	0.1655	0.1719	0.0880	0.0217
	1976	17.1505	0.1442	0.1601	0.1668	0.0863	0.0218
	1977	16.1662	0.1396	0.1558	0.1626	0.0848	0.0218
	1978	15.4514	0.1365	0.1528	0.1596	0.0835	0.0218
	1979	14.9687	0.1346	0.4508	0.1577	0.0827	0.0218
	1980	14.6845	0.1342	0.1503	0.1571	0.0822	0.0218
	1981	14.5446	0.1405	0.1547	0.1606	0.0821	0.0218
	1982	14.5036	0.1467	0.1592	0.1643	0.0823	0.0218
	1983	14.5415	0.1526	0.1635	0.1679	0.0823	0.0218
	1984	14.6372	0.1601	0.1692	0.1725	0.0832	0.0218
Strategy 3	1975	16.6288	0.1330	0.1508	0.1583	0.0843	0.0217
	1976	15.2169	0.1256	0.1443	0.1520	0.0823	0.0218
	1977	14.2058	0.1205	0.1395	0.1473	0.0806	0.0218
	1978	13.5473	0.1174	0.1364	0.1441	0.0791	0.0218
	1979	13.2171	0.1160	0.1347	0.1423	0.0781	0.0218
	1980	13.1374	0.1165	0.1346	0.1421	0.0775	0.0218
	1981	13.2192	0.1238	0.1396	0.1462	0.0773	0.0218
	1982	13.3840	0.1308	0.1446	0.1504	0.0773	0.0218
	1983	13.5889	0.1374	0.1494	0.1544	0.0776	0.0218
	1984	13.8163	0.1455	0.1554	0.1593	0.0780	0.0218
Strategy 4.1	1975	9.4046	0.1049	0.1202	0.1266	0.0683	0.0216
	1976	9.0501	0.1018	0.1174	0.1239	0.0675	0.0216
	1977	8.8739	0.0999	0.1155	0.1220	0.0667	0.0216
	1978	8.5566	0.0980	0.1123	0.1132	0.0637	0.0216
	1979	8.2965	0.0967	0.1094	0.1147	0.0609	0.0216
	1980	6.0656	0.0961	0.1073	0.1121	0.0585	0.0216
	1981	7.6505	0.0993	0.1082	0.1119	0.0565	0.0217
	1982	7.6334	0.1022	0.1092	0.1119	0.0546	0.0217
	1983	7.4085	0.1047	0.1100	0.1118	0.0534	0.0217
	1984	7.2013	0.1083	0.1118	0.1125	0.0523	0.0217
Standards		9.0	.08			.05	.03

Source: MATHAIR output

While concentrations are somewhat further reduced by S3, the analysis of S1 outcomes holds equally for S3.

The impact of S.4 is to further reduce the levels of all pollutants. CO concentrations are seen to decrease monotonically over time and the standard can be met by 1977. SO_x levels are slightly reduced since automobile use has diminished. Neither the OX standard nor the NO_x standard can be met. However, our overall evaluation for Chicago, as for all the other study regions, is that a program of even a modest level of pollution controls can significantly reduce ambient concentrations of the mobile source pollutants.

In this section we have discussed the impact of three control strategies on air quality. In the next section we analyze the benefits and costs of alternative strategies for the four study regions.

SECTION VIII

ESTIMATES OF BENEFITS AND COSTS FOR ALTERNATIVE STRATEGIES IN THE FOUR STUDY REGIONS

REVIEW OF BENEFIT AND COST COMPONENTS

Strategy Benefits and Costs for the Study Regions

The individual components of costs and benefits have already been discussed in Section V. To briefly review, however, the cost of an air pollution control strategy is the sum of:

- automobile and stationary source control device costs
- operating and maintenance costs for automobile and stationary source control devices, including the cost of increased (or decreased) gasoline consumption due to automobile control devices.
- the value to travelers of reduced (or enhanced) mobility.

The benefits of a strategy are the dollar value of reduced air pollution damage and damage avoidance costs for all damage categories and for all pollutants.

LOS ANGELES

We now turn to an analysis of the benefits and costs of selected strategies in Los Angeles, shown in Table 12. The dollar value of damages for the zero control strategy, SO, is given on the table because it provides the baseline for calculating the benefits attributable to the control strategies (S1, S2, S3, S4. 1), which have already been defined.*

One strategy, S2, involves higher costs and lower benefits than S3, and thus turns out not to be cost effective.** The difference between the two strategies is that S3 adds mandatory inspection and maintenance (I/M) for

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* As we noted earlier, benefits must be tallied by the model user by subtracting the damages attributable to a strategy from the damages of the zero control strategy.

** A similar result was found for the other study regions.

TABLE 12. BENEFITS AND COSTS FOR SELECTED STRATEGIES IN LOS ANGELES (1975 PRESENT VALUE IN BILLIONS OF 1973 DOLLARS)

Strategy	Damages	Benefits	Costs	Net Benefits (Benefits-Costs)
S0	7.8	---	---	---
S1	4.2	3.6	1.9	1.7
S2	3.03	4.76	2.6	2.2
S3	2.97	4.83	2.4	2.5
S4.1	2.5	5.3	3.6	1.7
S0 with transportation controls of S4.1	6.5	1.3	0.7	0.6

Source: MATHAIR output.

automobiles. An analysis of MATHAIR output shows that the predicted saving to motorists from improved gasoline mileage is greater than the cost of I/M; since I/M also reduces pollutant emissions, the net effect is that S3 dominates S2. One wonders, however, why motorists do not voluntarily have their automobiles inspected and maintained in light of the expected cost saving. One possible explanation is that the data on gasoline consumption savings and inspection and maintenance cost are in error.

Table 12 also shows that strategy S3 maximizes net benefits and thus is the optimal choice among the strategies considered.* The final row of the table reports the results of a "stand-alone transportation controls" strategy that will be discussed below.

NEW YORK

The benefits and costs of selected air pollution control strategies** for New York are shown in Table 13. For strategies S1, S3, and S4, the benefits are smaller and the costs are greater than for the corresponding strategies in Los Angeles. Furthermore, net benefits in New York are negative in all three cases.

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[*] If, however, a policy decision were made to require S4.1 because it comes nearer to meeting the air quality standards, net benefits would still be positive.

[**] Results of S2 will not be reported for the remaining study regions since it is not cost-effective.

TABLE 13. BENEFITS AND COSTS FOR SELECTED STRATEGIES IN NEW YORK (1975 PRESENT VALUE IN BILLIONS OF 1973 DOLLARS)

Strategy	Damages	Benefits	Costs	Net Benefits (Benefits-Costs)
S0	28.1	---	---	----
S1	25.2	2.9	3.3	-0.4
S3	24.6	3.6	4.1	-0.5
S4.1	23.3	4.9	6.6	-1.7
S0 with transportation controls of S4.1	27.9	2.3	1.7	0.7

Source: MATHAIR output.

Although a detailed comparison of the different strategy outcomes between regions would lie outside the scope of this study, an approximate evaluation of the underlying causes can be made. The benefit of a strategy that controls a single pollutant is the product of two terms: the dollar value of damage per unit of the pollutant and the reduction in the number of units of the pollutant emitted both by mobile and stationary sources.

Generalizing to the case of several pollutants, we developed some rough estimates of the two terms which show that the dollar value of damage per unit of pollutant is more than twice as great in Los Angeles as in New York* while the number of reduced units of pollutants in New York is only about fifty percent greater than in Los Angeles.** The product of the two terms is thus more than one-third greater in Los Angeles, accounting for the greater dollar benefit in that region.

Costs are essentially proportional to the number of automobiles and the number of stationary sources since these are the units on which control devices are installed. Control costs are almost twice as great in New York as in Los Angeles because there are about fifty percent more automobiles*** and more than twice the number of stationary sources**** in New York.

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* Estimated from base year data in Tables F-35 and F-37 of Appendix F.

** Estimated using MATHAIR outputs.

*** Table F-1 of Appendix F.

**** Judging from total emissions shown in Table F-28 of Appendix F.

In addition to explaining these results, we were prompted by the poor apparent performance of the control strategies in New York to investigate whether an even lower level of control would be beneficial. We tested an additional strategy involving stand-alone transportation controls; that is, the zero control strategy with the transportation controls of S4.1. The net benefits, seen in Table 13, are small but positive. This lenient[*] strategy appears optimal in New York.

The impact of stand-alone transportation controls in New York motivated us to test the impact of the strategy in Los Angeles; the results are shown in Table 12. While net benefits are also positive in Los Angeles, a greater level of control is optimal in that region.

WASHINGTON, D. C.

Benefits and costs for S1, S3, and S4.1 for Washington, D. C., are shown in Table 14. As in New York, net benefits are negative for the three strategies, implying that the optimal decision is to require no controls.[**]

TABLE 14. BENEFITS AND COSTS FOR SELECTED STRATEGIES IN WASHINGTON, D. C. (1975 PRESENT VALUE IN BILLIONS OF 1973 DOLLARS)

Strategy	Damages	Benefits	Costs	Net Benefits (Benefits-Costs)
S0	1.1	---	---	----
S1	0.5	0.6	0.75	-0.14
S3	0.5	0.7	0.78	-0.13
S4.1	0.3	0.8	1.2	-0.45

Source: MATHAIR output.

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[*] In this context lenient means both low cost and low benefit.

[**] We did not simulate the stand-alone transportation controls strategy in Washington, D. C. It is possible that such a lenient strategy would be beneficial.

Strategy benefits and costs are considerably lower in Washington, D. C. than in the other study regions. While the dollar value of damage per unit of pollutant is roughly comparable to that in New York, the initial level of pollution and thus the amount of reduced emissions both for mobile and stationary sources, is by far the lowest of all study regions. For this reason the benefits realized by control strategies are low. Similarly, because costs are proportional to the number of automobiles and of stationary sources, the small number of both of these sources of pollution in Washington, D. C. explains the low strategy costs.

We next sought to explain why the marginal impact of S1 was considerably greater than that of S3 by inspecting each control measure of the two strategies. In addition to moderate stationary source control, S1 requires that all the mobile source controls mandated between 1967 and 1974 be implemented, and that future automobiles have the characteristics of 1974 models. In contrast, S3 adds to S1 only two controls in addition to stricter stationary measures; I/M on all automobiles and the catalytic convertor on post-1974 automobiles. Therefore in the case of S1 the benefits and costs of stationary source controls form only a small proportion of total benefits and costs and the impact of the mobile source measures prevails. However the impact of the stationary source control measure prevails in the case of S3.

While the proportion of automobiles in Washington, D. C., relative to the other regions is small, the proportion of stationary sources is even smaller. For this reason, the benefits and costs of S3 are particularly low. While none of our strategies isolates the stationary source controls, our results corroborate the a priori judgment that these measures have the smallest impact in areas with a small inventory of stationary sources of pollution.

CHICAGO

Benefits and costs of S1, S3, and S4.1 for Chicago are shown in Table 15. While net benefits of all three strategies are positive and of similar magnitude, the optimal strategy of the three is S3.

We performed a rough analysis of the strategy costs and benefits, as we did for New York and Washington, D. C. Since the number of automobiles and stationary sources of pollution in Chicago is about half that in New York, this analysis suggests that costs in Chicago should be about half those in New York, as indeed a comparison of Table 15 and Table 13 shows them to be.

Comparison of the two tables also shows benefits in Chicago to be about eighty percent of those in New York. Since base year emission levels in Chicago are less than eighty percent of those in New York, it must be that the dollar value of damage per unit of pollutant is higher in Chicago. Rough estimates are not sufficiently detailed to permit direct verification, but it is probably a greater dollar value of damage per unit of pollutant in Chicago that accounts for the positive net benefits in Chicago.

TABLE 15. BENEFITS AND COSTS FOR SELECTED STRATEGIES IN CHICAGO (1975 PRESENT VALUE IN BILLIONS OF 1973 DOLLARS)

Strategy	Damages	Benefits	Costs	Net Benefits (Benefits-Costs)
S0	18.3	----	----	----
S1	16.0	2.3	1.9	0.46
S3	15.5	2.8	2.3	0.50
S4.1	14.1	4.2	3.7	0.48

Source: MATHAIR output.

SOME GENERAL IMPLICATIONS

The net benefits of strategies S1, S3, and S4.2 for the four study regions are assembled in Figure 9. Net benefits of all strategies are positive in Los Angeles and Chicago and negative in New York and Washington, D.C. and net benefits are highest in Los Angeles and lowest in New York. While care must be taken in generalizing the results of simulations in only four regions, we feel that some useful statements can be made about the reasons underlying these results.

Strategies Involving Pollution Control Devices

Strategies S1, S3, and S4.1 require pollution control devices for automobiles and stationary sources. The costs of the strategies are plotted in Figure 10 as a function of the size of the 1975 automobile stock and in Figure 11 as a function of the number of units of stationary source pollution.*

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* For each type of stationary source (e.g., airport ground operations), the number of units is equal to total emissions of that type of source in a given region divided by the emissions of a "typical" unit (e.g., ground operations at an average size airport). For purposes of Figure 11, units are totaled over all types of stationary sources.

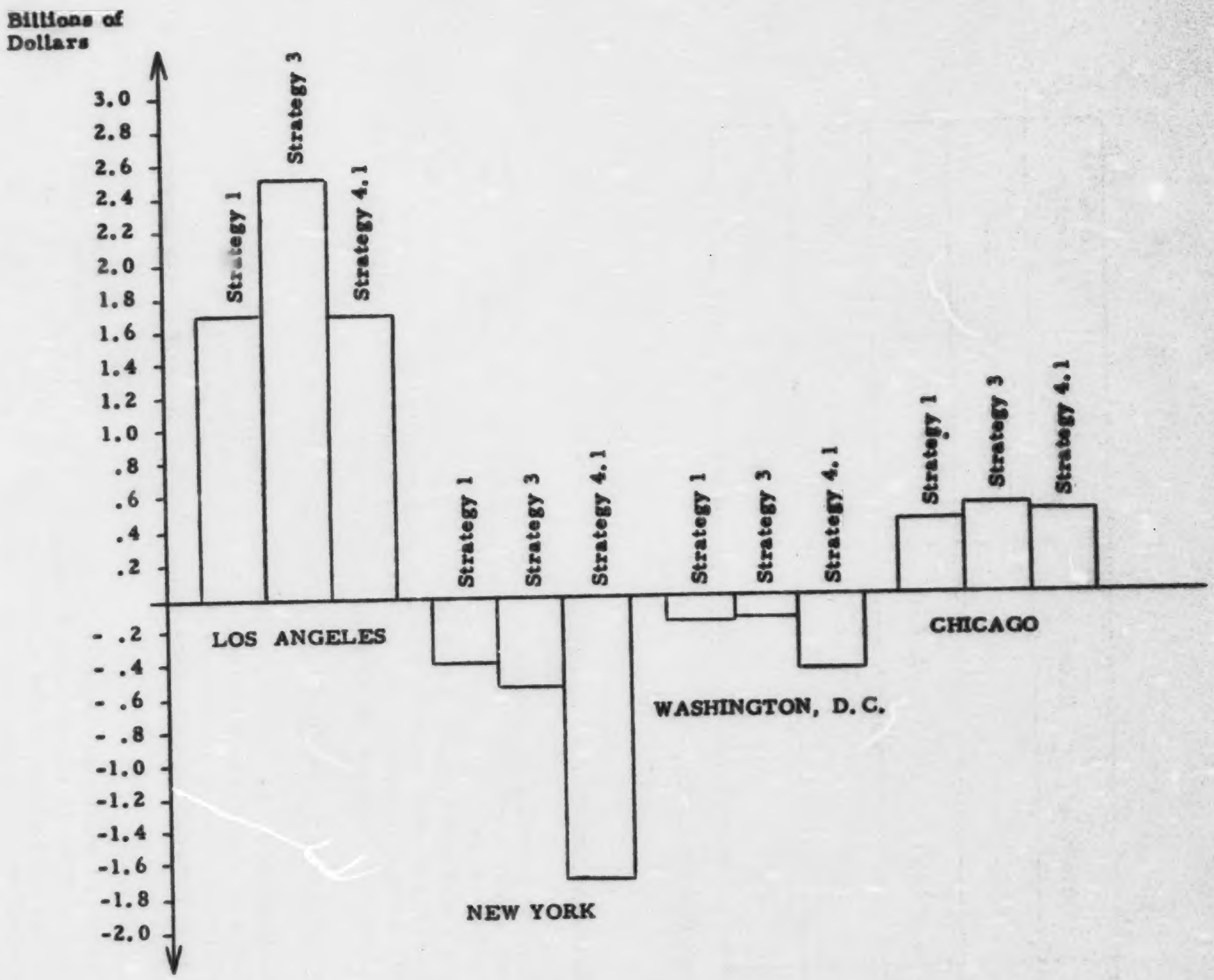

Figure 9. Net benefits of selected strategies in the four study regions.

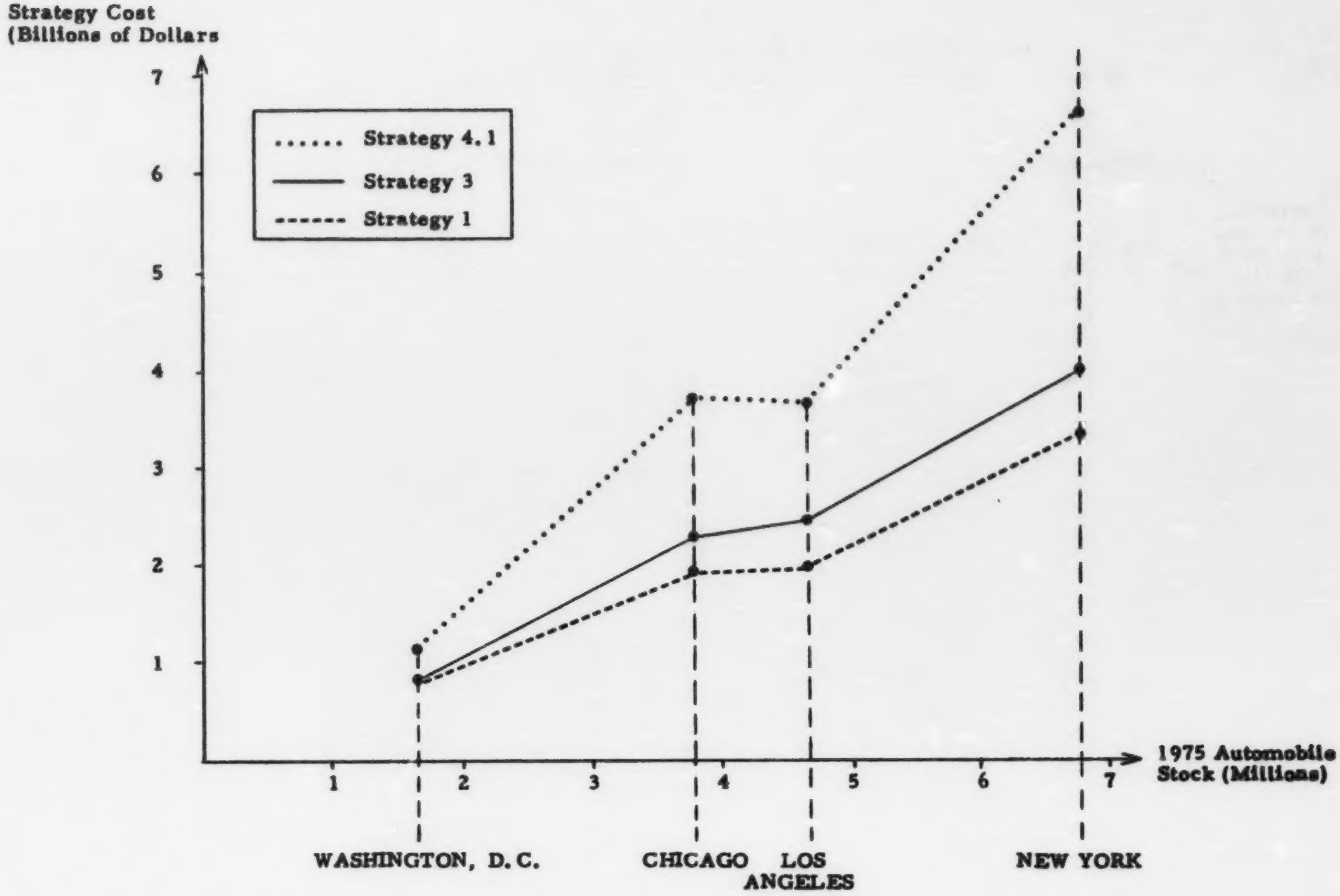

Figure 10. Costs of selected strategies as a function of 1975 automobile stock in the four study regions.

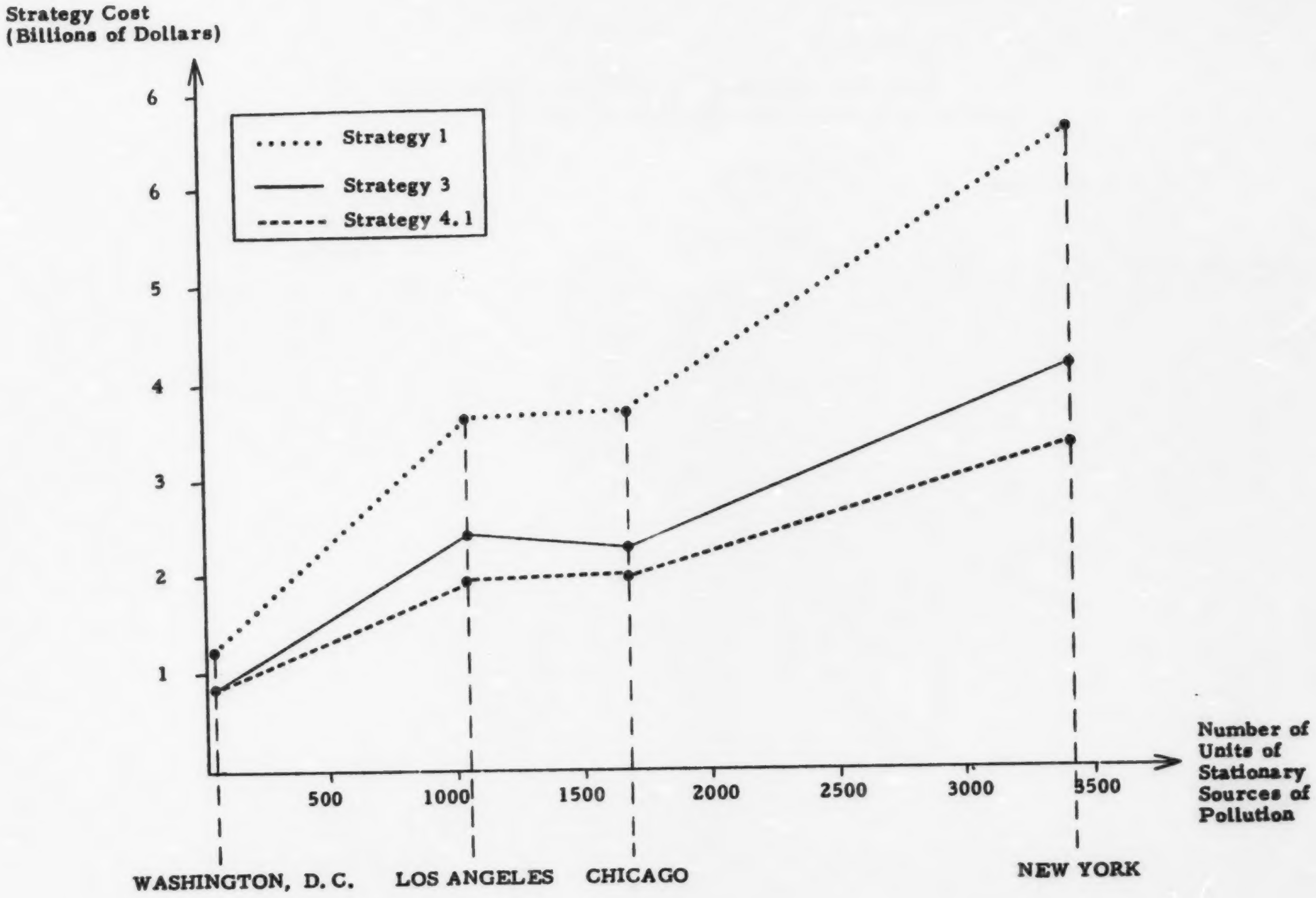

Figure 11. Costs of selected strategies as a function of number of units of stationary sources of pollution in the four study regions.

It is hardly surprising that costs for all strategies increase with the number both of automobiles and of stationary sources since costs are incurred on a per unit basis. However, while the total (and marginal) costs of S1 and S3 in all regions are in line with the size of the automobile stock, the total (and marginal) benefits and the ratios of marginal benefits to marginal costs for both strategies S1 and S3* are highest in Los Angeles. One reason, that has already been discussed, is that the dollar value of damage per unit of pollution is higher in Los Angeles than in the other study regions. A second reason lies in the intensity of automobile use. To illustrate this notion, suppose that there are the same number of automobiles in two different regions, A and B, but that the average automobile in A is driven twice as many miles and thus emits twice the quantity of pollutants as an average automobile in B. Now let us assume that an air pollution control device that reduces emissions by 10% is installed on all automobiles in both regions. Since there are the same number of automobiles in both regions, air pollution control device costs will be the same in A as in B. However, for the given percentage decrease in emissions, the reduction of units of pollutant emitted in A will be twice as large as in B. If all other things are equal, in particular, the dollar value of damage per unit of pollutant, the larger reduction in emissions will translate into a larger dollar amount of benefits. This means that the dollar benefit produced by mobile source control devices per dollar of cost will be greater in a region where automobiles are driven intensively than they are in other regions.

Data on the average daily miles driven by an automobile in Los Angeles, New York, Washington, D. C., and Chicago, given in Table 16, indicate that automobiles are driven most intensively in Los Angeles and least intensively in Washington, D. C. This ranking is consistent with the ranking of marginal benefits and with the ranking of the dollar benefit per dollar of cost.

TABLE 16. SELECTED AUTOMOBILE USE STATISTICS FOR THE STUDY REGIONS

	1975 Daily Auto Miles Traveled[a]	1975 Automobile Stock	Average Daily Miles Per Auto
Los Angeles	159	4,680,750	34.0
New York	200	6,777,545	29.5
Washington, D. C.	36.5	1,694,500	21.5
Chicago	113	3,831,175	29.5

Source: All numbers are calculated from data in Appendix F.

[a] millions of miles.

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* Strategy S4.1, which involves transportation controls as well as hardware devices, is discussed in the next part of this section.

While it is true that strategies S1 and S3 include moderate stationary source controls as well as automobile controls, we conclude that one component of the large net benefits seen in Los Angeles for strategies requiring automobile pollution control devices is the relative intensity of automobile use in that region and that automobile control devices are more likely to be beneficial in high-pollution regions like Los Angeles where the automobile is used intensively than in areas with low pollution and low intensity automobile use. This does not mean that all pollution control devices are beneficial. For example, we calculated the benefits and costs for Los Angeles of a new strategy which adds the three-way catalytic convertor* to the control measures of S3. The marginal cost was about twice the marginal benefit, indicating that the usefulness of a device depends upon its cost and control characteristics and upon the level of control that has already been attained.

Strategies Involving Transportation Control Measures

The fourth strategy adds three controls to S3: the three-way catalytic convertor for new post-1978 autos, several retrofit devices for in-use autos, and a transportation control measure (50 percent increase in per mile auto cost). The marginal costs of this strategy are greater than the marginal benefits in all four study regions. However, both the marginal benefits and the ratio of marginal benefits to marginal costs are highest in Chicago and New York.

The data on changes in transportation patterns of the four regions, given in Table 17, suggest that the key to these results lies in the different natures of the transportation systems. The increased cost of automobile transportation leads to a 25-30 percent decline in automobile passenger trips in Chicago and New York, well above the 12-18 percent decline in Los Angeles and Washington, D. C. Furthermore a much smaller fraction of these foregone automobile trips are replaced by bus trips in Chicago (27 percent) and New York (11 percent) than in Los Angeles (41 percent) and Washington, D. C. (50 percent). Thus there is very little pollution offset from increased bus pollution in the first two cities.

However, Chicago and New York differ substantially in the allocation of the remaining foregone trips. In Chicago 35 percent of the foregone trips are switched to rail, so that only 38 percent of the reduced automobile trips represent cancelled trips. On the other hand, in New York only 12 percent of the foregone trips are switched to rail, meaning that 77 percent of the reduced automobile trips represent cancelled trips. The differences are even more striking when the changes in trips are disaggregated by trip purpose and mode as shown in Table 18 for Chicago and New York.

The fraction of foregone automobile trips represented by foregone work trips is about the same for Chicago (15%) and New York (19%). In both cities, about forty five percent of the work trips formerly made by automobile are now made by rail. The real difference lies in the foregone

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* This device is relatively expensive and effective. Its characteristics are shown in Table F-41 in Appendix F.

TABLE 17. SELECTED TRANSPORTATION CONTROL SIMULATION OUTPUTS FOR THE FOUR STRATEGY REGIONS (ALL FIGURES ARE ON A DAILY BASIS)

	Bus and Rail Miles As a Proportion of Automobile Miles (1)	Reduction in Automobile Passenger Trips Due to Strategy 4.1. % reduction shown in parentheses (2)	Increase in Bus Passenger Trips Due to Strategy 4.1 (3)	Increase in Rapid Transit Passenger Trips Due to Strategy 4.1 (4)	Fraction of Foregone Automobile Trips Switched to Bus (5) = $\frac{(3)}{(2)}$	Fraction of Foregone Automobile Trips Switched to Bus and Rail (6) = $\frac{(3)+(4)}{(2)}$
Los Angeles	.0015	1,520,000 (12.6)	630,000	-	.41	.41
New York	.0090	3,940,000 (25.8)	422,000	470,000	.11	.23
Washington, D.C.	.0027	420,000 (17.5)	212,000	-	.50	.50
Chicago	.0085	2,350,000 (28.3)	639,000	810,000	.27	.62

Source: MATHAIR outputs

TABLE 18. SELECTED TRANSPORTATION CONTROL SIMULATION OUTPUTS FOR NEW YORK AND CHICAGO DISAGGREGATED BY TRIP PURPOSE (FIGURES ARE ON A DAILY BASIS)

	Reduction in Automobile Passenger Trips	Increase In Bus Passenger Trips	Increase In Rail Passenger Trips	Cancelled Trips *
New York				
Work Trips	750,000	422,000	330,000	0
Shopping Trips	1,390,000	0	90,000	1,300,000
Other Trips	1,800,000	0	50,000	1,750,000
Total	3,940,000	422,000	470,000	3,048,000
Chicago				
Work Trips	357,000	195,000	162,000	0
Shopping Trips	513,000	126,000	124,000	263,000
Other Trips	1,479,000	318,000	527,000	634,000
Total	2,349,000	639,000	812,000	898,000

Source: MATHAIR outputs.

* Figures may not add exactly to totals shown in the last column of this table or in Table 17 due to rounding.

automobile trips for other purposes. In Chicago about 55 percent of these trips are replaced by bus or rail trips while the percent in New York is negligible. We can only speculate about the source of these differences. One possible explanation is that substitution possibilities between automobiles and mass transportation exist in Chicago while in New York the automobile is reserved for situations when substitution by mass transit is difficult.

A contributing factor to the relatively high marginal benefits of S4.1 in New York and Chicago (or, more exactly, to the relatively low benefits in Los Angeles) is the time of day of most transfers from automobile to mass transportation. In these two regions (and in Washington, D. C.), mass transportation is heavily used for work-trips (shown in Table 19) at peak hour occupancy rates. By contract, bus transportation is little used for work trips in Los Angeles, thus reducing the average bus occupancy rate* below that of the other regions. Transfer of a given number of passengers to bus therefore requires more buses, involving more pollution, than in the other regions.

TABLE 19. WORK TRIP BY MODE CHOICE FOR THE FOUR STUDY REGIONS (1970 data)

	% of Employed Central City Residents Using:		% of Employed Non-Central City Residents Using:	
	Auto	Transit	Auto	Transit
New York	30	70	82	18
Chicago	60	40	88	12
Washington, D. C.	57	43	91	9
Los Angeles	90	10	97	3

Source· Calculated from AIP-MVMA, Urban Transportation Factbook (1974), p. I-22, assuming that all work trips use either automobile or mass transit.

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[*] MATHAIR uses a peak bus-occupancy rate for work trips and an off-peak rate for shopping and other trips. These two rates remain constant even if demand for bus trips increases.

In sum, our analysis suggests that automobile use restrictions may be relatively successful in regions with well-developed networks of mass transportation for two reasons: first, travellers are more likely to forego the trip by automobile. Second, they are less likely to switch to bus, the second most polluting means of transportation.

SECTION IX

SENSITIVITY ANALYSIS

INTRODUCTION

An important step in the development of any simulation model is to test the sensitivity of the model to changes in the variables and parameters. Sensitivity results indicate the stability of the model's calculations with respect to changes in the data, identifying those data series for which small variations may have a significant impact on the simulation outcomes. In this section we report the results of a limited sensitivity analysis of the MATHAIR model.

- In the first case, strategies S1, S3, and S4.1 are simulated for all four study regions using an accelerated rate of removal of automobiles from the stock.
- Strategies S1, S3, and S4.1 are simulated for Los Angeles making some "worst case" assumptions about several variables.
- Two alternative transportation control measures are defined, and strategies S4.2 and S4.3 are constructed by substituting these new measures for the transportation controls of S4.1. Outcomes for the three strategies are compared for Los Angeles and New York.

ACCELERATED RATE OF REMOVAL FROM AUTOMOBILE STOCK

Nature of the Change

An input to MATHAIR's Automobile Stock Module is the automobile scrappage rate. Strategies S1, S3 and S4.1 were simulated for all four regions using a dramatically accelerated automobile scrappage rate. Specifically, the proportion of automobiles i years old still on the road, P_i, was assumed to be given by

$$P_i = \prod_{k=1}^{i} P_k'$$

where P'_k is the proportion still on the road after k years in the standard case. The impact of this substitution is indicated by Table 20, which gives the values of P_i and P'_i. The effects of this change in scrappage rate are:

- reduced size of automobile stock
- reduced proportion of older automobiles in stock
- increased number of miles driven per automobile.

TABLE 20. PERCENTAGE OF AUTOMOBILES OF GIVEN AGE STILL IN THE STOCK

Age of Automobile	Standard Case (P_i)	Assuming Accelerated Scrappage Rate (P'_i)
1	1 100.0	100.0
2	2 99.0	99.0
3	3 98.0	97.0
4	4 96.0	93.1
5	5 92.0	85.7
6	6 85.0	72.8
7	7 74.0	53.9
8	8 60.0	32.3
9	9 44.0	14.2
10	10 32.0	4.6
11	11 23.0	1.1
12	12 17.0	0.2
13	13 12.0	0.0
14	14 9.0	0.0
15	15 6.0	0.0
16	16 4.0	0.0
17	17 3.0	0.0
18	18 2.0	0.0
19	19 1.0	0.0
20	20 0.5	0.0

Impacts on Benefits and Costs

The benefits and costs for strategies S1, S3, S4.1, calculated with the accelerated scrappage rate schedule, are shown in Table 21 with net benefits for the standard case in parentheses.* Accelerating the scrappage rate results in somewhat lower costs, higher benefits and thus higher net benefits than in the standard case. Lower costs clearly result from the reduced size of the automobile stock and, in particular, a smaller number of automobiles with pollution control devices. Because the average automobile is driven more miles than in

TABLE 21. BENEFITS AND COSTS FOR SELECTED STRATEGIES IN THE FOUR STUDY REGIONS ASSUMING AN ACCELERATED SCRAPPAGE RATE (1975 PRESENT VALUE IN BILLIONS OF 1973 DOLLARS)

	Costs	Damages	Benefits	Net Benefits*
Los Angeles				
Strategy 0		7.8		
Strategy 1	1.7	3.9	3.8	2.1 (1.7)
Strategy 3	2.3	2.7	5.1	2.9 (2.5)
Strategy 4.1	3.4	2.3	5.5	2.1 (1.7)
New York				
Strategy 0		28.1		
Strategy 1	3.0	25.0	3.1	0.2 (- .4)
Strategy 3	3.9	24.3	3.8	-0.1 (- .5)
Strategy 4.1	6.3	23.1	5.0	-1.3 (-1.7)
Washington, D.C.				
Strategy 0		1.1		
Strategy 1	0.68	0.5	0.6	-0.04 (-.14)
Strategy 3	0.73	0.4	0.7	-0.04 (-.13)
Strategy 4.1	1.1	0.3	0.8	-0.3 (-.5)
Chicago				
Strategy 0		18 3		
Strategy 1	1.7	15.8	2.5	0.81 (.46)
Strategy 3	2.2	15.2	3.0	0.83 (.50)
Strategy 4.1	3.7	14.0	4.3	0.6 (.48)

*Numbers in parentheses are the net benefits in the standard case from Tables 12 to 15.

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*Corresponding benefits and costs for the standard case are reported in Tables 12 through 15.

the standard case, each automobile causes more pollution. Therefore, a given percentage decrease in automobile emissions from a control device will mean more units of pollution reduction than in the standard case. Since the benefits of a strategy equal the product of the dollar damage per unit of pollutant and the number of units of pollutant reduced by the strategy, benefits are higher in the case of the accelerated scrappage rate.* The optimal strategies in Los Angeles, Chicago and Washington remain unchanged (S3 for Los Angeles and Chicago and no controls for Washington). In New York, the net benefits for S1 are now positive and this strategy is preferable to one involving zero controls.

We conclude that small variations in the scrappage rate will have only a small impact on strategy outcomes since even the steeply accelerated scrappage rate we have simulated produced a relatively minor impact.

A "WORST CASE" CALCULATION FOR LOS ANGELES

Nature of the Change

Several of data series input to MATHAIR are subject to considerable uncertainty. This is evidenced by official "up-dates" which often represent significant changes in the series and by widely different estimates obtained by different researchers. As an example of how the model's results can be sensitive to data uncertainty, we conducted simulations for Los Angeles based on a set of "worst case" assumptions. These assumptions, designed to reduce benefits and increase cost, are as follows:

- 10% increase in costs of emission control devices
- lower base year damage estimates
- decreased automobile control drive efficiencies

The meaning of the first is straightforward. The other two assumptions require explanation. The base year damage estimates used in the standard case simulations are based upon estimates of Barrett and Waddell extended by Babcock and Nagda.** However, Justus et al. propose a range of nationwide estimates that are considerably lower.*** For our "worst case" simulations, we have used Justus's "lower bound" estimates, which are less than twenty percent of the standard case estimates. Low estimates of pollution damage in the base year mean a low damage cost per unit of pollution and hence a low benefit per unit of pollutant reduced by a control strategy.

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* This argument was also made for Los Angeles in Section VIII.

** Reported in C.G. Justus, J.R. Williams, and J.D. Clement, Economic Costs of Air Pollution Damage, prepared for Southern Services, Inc., Birmingham, Alabama (May 1973).

*** Justus et al., ibid. Both sets of estimates are shown in Tables F-35 and F-36 of Appendix F.

The automobile emission characteristics used in the standard case are from the EPA report Compilation of Air Pollution Emission Factors - AP42 (April 1973), as updated (Supplement No. 2, September 1973). An unedited preliminary edition of Supplement No. 5 has recently been made available (April 16, 1975). In this document, the approach to calculating mobile source pollutants has been modified in several ways. Most significantly, measured and estimated new car emissions for recent vintages have been increased considerably (over AP42 estimates) and, at least for California, reported new car emissions no longer show a monotonic decrease for more recent model years.* If these new estimates are correct, it means that automobile control devices employed since 1967 (1965 in California) have not been as effective as previously claimed.

We have not incorporated the changes in Supplement No. 5 into our standard case both because of the tentative nature of the data and because the level of effort required would be prohibitive for a project near completion. However, for purposes of the "worst case" sensitivity analysis, we have developed a set of emission characteristic estimates based on Supplement No. 5.** While these estimates are monotonic (decreasing with more recent vintage year), they do reflect the higher emission levels*** of the more recent document. Emissions under the zero control strategy will be the same as in the standard case, but other strategy outcomes should be affected in two ways: air quality will deteriorate relative to the standard case, and benefits should decrease. The latter consequence results from a smaller number of units of pollutant reduction.

The scenario incorporating these three kinds of data changes is a "worst case" from the point of view of air pollution control because each change contributes to a deterioration of air quality, an increase in strategy costs and/or a reduction of strategy benefits.

Impacts on Air Quality

MATHAIR air quality predictions for the "worst case" are shown in Table 22 along with the air quality standards. Pre-control air quality, corresponding to the zero control strategy, is the same as in the standard case. Air quality under strategies S1, S3, and S4.1 can be compared against the standard case results for Los Angeles shown in Table 8.

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* For example, new car CO emissions for California are reported in Supplement No. 5 as follows (based on 1975 Federal Test Procedure):

1971	42.3 gr/mi (measured, p. 33).
1972	46.7 gr/mi (measured, p. 35).
1973	37.0 gr/mi (estimated, p. D10).

** These estimates and the standard case automobile emission estimates are shown in Tables F-21 and F-22 of Appendix F.

*** For 1975 models driven in California, for example, Supplement No. 5 estimates of emissions per mile of CO, HC, and NO_x are more than 75% higher than corresponding estimates in Supplement No. 2.

TABLE 22. AIR QUALITY IN LOS ANGELES FOR SELECTED STRATEGIES USING "WORST CASE" AUTOMOBILE POLLUTANT EMISSIONS CHARACTERISTICS (PPM)

Strategy	Year	Carbon Monoxide (CO)	Oxidants (OX)			Nitrogen Oxide (NOX_x)	Sulfur Oxides (SOX_x)
Zero Control Strategy	1975	54.7388	0.5096	0.4720	0.4483	0.0637	0.0158
	1976	55.7445	0.5169	0.4786	0.4544	0.0645	0.0158
	1977	56.7804	0.5246	0.4855	0.4607	0.0653	0.0158
	1978	57.8472	0.5326	0.4926	0.4672	0.0662	0.0159
	1979	58.9462	0.5409	0.5000	0.4740	0.0671	0.0159
	1980	60.0681	0.5495	0.5077	0.4811	0.0680	0.0159
	1981	61.2439	0.5585	0.5156	0.4883	0.0689	0.0159
	1982	62.4447	0.5677	0.5238	0.4958	0.0699	0.0160
	1983	63.6815	0.5773	0.5323	0.5036	0.0709	0.0160
	1984	64.9555	0.5872	0.5410	0.5116	0.0720	0.0160
Strategy 1	1975	38.8726	0.2900	0.3285	0.3428	0.0654	0.0158
	1976	37.5759	0.2761	0.3188	0.3340	0.0652	0.0158
	1977	36.6050	0.2660	0.3188	0.3276	0.0651	0.0158
	1978	36.0123	0.2597	0.3078	0.3240	0.0653	0.0159
	1979	35.7826	0.2560	0.3063	0.3228	0.0657	0.0159
	1980	35.7810	0.2543	0.3062	0.3230	0.0662	0.0159
	1981	35.9872	0.2564	0.3091	0.3260	0.0669	0.0159
	1982	36.3410	0.2797	0.3263	0.3425	0.0677	0.0160
	1983	36.8083	0.3015	0.3427	0.3579	0.0686	0.0160
	1984	37.3665	0.3218	0.3582	0.3722	0.0695	0.0161
Strategy 3	1975	32.1118	0.2477	0.2908	0.3056	0.0609	0.0158
	1976	27.4362	0.2205	0.2671	0.2819	0.0582	0.0158
	1977	22.9741	0.1974	0.2465	0.2609	0.0557	0.0158
	1978	19.1371	0.1791	0.2300	0.2439	0.0536	0.0159
	1979	16.0006	0.1647	0.2173	0.2307	0.0522	0.0159
	1980	13.5364	0.1539	0.2079	0.2207	0.0511	0.0159
	1981	11.8848	0.1491	0.2037	0.2162	0.0506	0.0159
	1982	10.6463	0.1665	0.2149	0.2280	0.0504	0.0160
	1983	9.8661	0.1835	0.2266	0.2396	0.0505	0.0160
	1984	9.3433	0.1998	0.2380	0.2507	0.0508	0.0161
Strategy 4.1	1975	18.8779	0.1944	0.2397	0.2535	0.0534	0.0156
	1976	16.6658	0.1776	0.2246	0.2380	0.0515	0.0156
	1977	14.5358	0.1635	0.2115	0.2244	0.0497	0.0157
	1978	12.3258	0.1508	0.1942	0.2060	0.0454	0.0157
	1979	10.4562	0.1407	0.1795	0.1903	0.0416	0.0157
	1980	8.8932	0.1328	0.1672	0.1771	0.0381	0.0158
	1981	7.7781	0.1291	0.1592	0.1684	0.0355	0.0158
	1982	6.9082	0.1425	0.1637	0.1713	0.0333	0.0158
	1983	6.3176	0.1555	0.1691	0.1746	0.0317	0.0158
	1984	5.9131	0.1679	0.1753	0.1785	0.0306	0.0159
Standards		9.0	.08			.05	.03

Source: MATHAIR outputs

While there is considerable pollution reduction with respect to the zero controls levels, the "worst case" results for S1 show no further improvement in air quality over the 1975 to 1984 simulation horizon. After a small initial decline, concentrations of all pollutants increase and, except for carbon monoxide, eventually exceed the 1975 levels. The reduction in pollution due to devices required by S1 is apparently offset by pollution increases from the growing use of automobiles with "worst case" emission characteristics.

None of the air quality standards can be met by S1 in either the standard case or the "worst case." Strategy S3, by contrast, effects significant pollutant concentration reductions in both cases. Still, the standards for CO, OX, and NO_x cannot be met in the "worst case" while only the OX standard is not met in the standard case. Strategy S4.1 also results in a significant reduction in pollutant concentrations in both cases. While concentrations of all pollutants are higher than in the standard case, in both cases all standards, except that for oxidants, can be met by 1984.

The "worst case" assumes reduced efficiencies for all automobile pollution control devices specified in strategy S1. The efficiencies of devices for new automobiles built after 1975 and of retrofit devices for old automobiles specified by strategies S3 and S4.1 are not reduced by the "worst case" assumptions. Hence, the latter two strategies are more effective in improving air quality.

Impacts on Strategy Benefits and Costs

Table 23 shows the benefits and costs of S1, S3, and S4.1 using "worst case" assumptions in Los Angeles (with net benefits under the standard case given in parentheses). As anticipated, control costs for all strategies are 10% higher in the "worst case." "Worst case" benefits are considerably lower than standard case benefits for all strategies, reflecting both the decreased value per unit of pollutant reduction and the smaller number of units reduced.

TABLE 23. BENEFITS AND COSTS FOR SELECTED STRATEGIES IN LOS ANGELES USING "WORST CASE"* ASSUMPTIONS (1975 PRESENT VALUE IN BILLIONS OF 1973 DOLLARS)

	Costs	Damages	Benefits	Net Benefits**
Strategy 0		1.0		
Strategy 1	2.1	0.6	0.4	-1.7 (1.7)
Strategy 3	2.6	0.4	0.6	-2.0 (2.5)
Strategy 4.1	4.0	0.3	0.7	-3.3 (1.7)

*
- 10% control device cost increases
- Justus lower bound damage estimates
- Emissions adapted from Supplement No. 5 to AP 42.

**Numbers in parentheses are standard case results from Table 12.

While all strategy benefits are greater than the corresponding costs in the standard case, all "worst case" strategy costs are greater than the corresponding benefits. The optimal strategy is to require no controls, and this remains true even if costs are not increased by ten percent.

We conclude that if the California standard case efficiencies of automobile control devices and the base year estimates of damage due to air pollution are seriously overestimated, the benefits due to strategies like those we have considered are equal to only a fraction of their cost.

THREE TRANSPORTATION CONTROL MEASURES IN LOS ANGELES AND NEW YORK

Nature of the Measures

Our most stringent strategy, S4.1, includes a transportation control measure involving a fifty percent increase in the cost per mile of using the automobile. In order to test the sensitivity of MATHAIR to different transportation controls, we have devised two other versions of S4, S4.2 and S4.3, involving the following transportation controls:

S4.2	Bus fares decreased by one-third through a government subsidy
S4.3	Cost per mile of automobile use increased by half and bus fares decreased by one-third.

Impact on Benefits and Costs

The benefits and costs of strategies S4.1, S4.2, and S4.3 for Los Angeles and New York are shown in Table 24. The benefits attributable to each strategy, in both regions, are about the same (five billion dollars). While the costs in New York are also comparable for the three strategies, S4.3 is considerably more costly than the other strategies in Los Angeles.

In Los Angeles, the net benefits of S4.1 and S4.2 are positive while the costs of S4.3 are slightly higher than the benefits. The optimal choice among the three strategies is S4.2, but the optimal choice among all strategies simulated is still S3.

In New York, the net benefits are negative for all three strategies. However, as in Los Angeles, the best (or least undesirable) choice of the three is S4.2 and the most costly is S4.3.

It is often said that effective transportation controls should include a constraint on the use of automobiles. While our results show decreased bus costs (S4.2) to be more beneficial than increased automobile costs (S4.1), this may be due to the magnitude of cost changes selected for our simulations. However, the least beneficial of the three measures is the simultaneous change in both costs indicating that more transportation controls are not necessarily better than fewer.

TABLE 24. BENEFITS AND COSTS OF THREE TRANSPORTATION MEASURES IN LOS ANGELES AND NEW YORK (1975 PRESENT VALUE IN BILLIONS OF 1973 DOLLARS)

	Costs	Damages	Benefits	Net Benefits
Los Angeles				
Strategy 0		7.8		
Strategy 4.1	3.6	2.5	5.3	1.71
Strategy 4.2	3.1	2.4	5.1	1.95
Strategy 4.3	5.2	2.6	5.2	-0.02
New York				
Strategy 0		28.1		
Strategy 4.1	6.6	23.3	4.9	-1.77
Strategy 4.2	5.3	23.7	4.4	-0.87
Strategy 4.3	6.8	23.1	5.0	-1.80

SECTION X

REFERENCES

Environmental Protection Agency

Aircraft Emissions: Impact on Air Quality and Feasibility of Control, (undated, assumed 1972).

Air Quality Data, 1972 Annual Statistics, EPA-450/a-74-001 (March 1974).

Barrett, L. B. and N. L. Nagda, "The Cost of Air Pollution Damage: A Status Report," (1971), cited in Justus, C.G., J.R. Williams, and J.D. Clement, Economic Costs of Air Pollution Damage, STAR, Inc. (May 1973).

Compilation of Air Pollution Emission Factors, AP-42 (April 1973), Supplement No. 2 (September 1973) and Supplement No. 5 (April 1975).

The Cost of Clean Air, Annual Report of the Administrator Environmental Protection Agency to the Congress of the United States (April 1974).

Crenshaw, J. and A. Basala, "Analysis of Control Strategies to Attain the National Ambient Air Quality Standard for Nitrogen Dioxide," presented to the Washington Operation Research Council's Third Cost-Effectiveness Symposium, National Bureau of Standards (1974).

Heavy Duty Vehicle Driving Pattern and Use Survey - New York City, prepared by Wilbur Smith and Associates, APTD-1523 (May 1973).

Hydrocarbon Pollutant Systems Study, EPA Contract No. 71-12, MSA Research Corporation, Vol. 1 (1972).

Horowitz, J., "Transportation Controls," prepared for publication in Environmental Science and Technology (1974).

Horowitz, J. and S. Kuhrtz, Transportation Controls to Reduce Automobile Use and Improve Air Quality in Cities, EPA-400/11-74-002 (1974).

1975 County Emissions Summary Reports, National Emissions Data System.

Prediction of the Effects of Transportation Controls on Air Quality in Major Metropolitan Areas, APTD-1363 (November 1972).

Stationary Internal Combustion Engines in the U.S. (1973).

Systems and Costs to Control Hydrocarbon Emissions From Stationary Sources, Emission Standards and Engineering Division (August 1973).

Technical Support Document for the Metropolitan Los Angeles Intrastate Air Quality Control Region Transportation Control Final Promulgation, Region IX (October 30, 1973).

Transportation Control Strategy Development for the Metropolitan Los Angeles Area, APTD-1372 (December 1972).

Transportation Control Strategy Development for the New York Metropolitan Area, APTD-1371 (December 1972).

Waddell, J., Economic Damages of Air Pollution (1974).

Other References

Auto Facts and Figures, Motor Vehicle Manufacturers Association, (1972 and 1973 editions).

Babcock, L.R. and N.L. Nagda, "Cost Effectiveness of Emission Control," Journal of the Air Pollution Control Association, 23, 173-179 (1973) cited in Justus, C.G., J.R. Williams, and J.D. Clement, Economic Costs of Air Pollution Damage, STAR, Inc. (May 1973).

Bostich, T.A. and H.J. Greenbalgh, Relationships of Passenger Car Age and Other Factors to Mileage Driven, Washington, D.C.: U.S. Department of Commerce, Bureau of Public Roads (1967).

Control Techniques for Nitrogen Oxide Emissions from Stationary Sources, U.S. Department of Health, Education and Welfare, (March 1970).

Domencich, T.A. and D. McFadden, A Disaggregated Behavioral Model of Urban Travel Demand, Cambridge, Mass., Charles River Associates, Inc. (March 1972).

Federal Register, Vol. 7, No. 36, "Proposed Rule-Making: Regulation of Fuels and Fuel Additives," (1972).

Goeller, B.F. et al., San Diego Clean Air Project, The RAND Corporation, R-1362-SD (December 1973).

Ingram, G.K., and G.R. Fauth, TASSIM: A Transportation and Air Shed Simulation Model, U.S. Department of Transportation (May 1974).

Justus, C.G., J.R. Williams, and J.D. Clement, Economic Costs of Air Pollution Damage, STAR, Inc. (May 1973).

McFadden, D. and F. Reid, Aggregate Travel Demand Forecasting From Disaggregated Behavioral Models (February 1974, revised).

Mikolowsky, W. T. et al., The Regional Impacts of Near-Term Transportation Alternatives: A Case Study of Los Angeles, the RAND Corporation, R-1524-SCAG (June 1974).

Moran, John B., Lead in Gasoline: Impact of Removal on Current and Future Automotive Emissions, for Air Pollution Control Association (1974).

Motor Truck Facts, Motor Vehicle Manufacturers Association, (1973).

Report by the Committee on Motor Vehicle Emissions, National Academy of Sciences, (November 1974).

Status of Regional Public Transportation Service and Use, Tri-State Regional Planning Commission (May 1974).

Stoddard, L. and P. Downing, The Economics of Air Pollution Control for Used Cars, Riverside: University of California, working paper No. 15.

A Survey of Average Driving Patterns in Six Urban Areas of the United States, System Development Corporation, (1971).

Ter Haar et al., "Composition, Size, and Control of Automotive Exhaust Particulates," APCA Journal, Vol. 22, No. 1 (January 1972).

Turner, D. B., Workbook of Atmospheric Dispersion Estimates, U.S. Department of Health, Education and Welfare, (March 1970).

Urban Transportation Factbook, American Institute of Planners - Motor Vehicle Manufacturers Association, (1974).

Vehicle Miles of Travel on Major Roadways: 1970, Tri-State Regional Planning Commission, (November 1973).

APPENDIX A

METRIC CONVERSIONS

1. Conversion of parts per million (ppm) micrograms per cubic meter ($\mu g/m^3$) for five pollutants.

	1 ppm in $\mu g/m^3$
Carbon Monoxide	1140
Hydrocarbons	667
Oxidants	2000
Nitrogen oxides	2000
Sulfur oxides	2600

2. Conversion of grams per mile (gr/mi) to grams per kilometer (gr/km).

1 gr/mi = 1.6 gr/km

3. Conversion of tons (T) to kilograms (kg).

1T = 907 kg

APPENDIX B

DESCRIPTION OF MATHAIR

In this appendix we provide the equations for the following six MATHAIR modules:

- Automobile Stock Module
- Transportation Module
- Emissions Module
- Air Quality Module
- Benefits Module
- Cost Module

MATHAIR user documentation is given in Appendix H.

AUTOMOBILE STOCK MODULE

The following four equations define the structure of this module:

(A.1) $VEH_{byr,j} = REG_{byr-j+1} \times \prod_{i=1}^{j} JUNK;$ (for base year only)

(A.2) $VEH_{y1} \times (1 + GROW)^{(y-byr)};$ (for new cars only)

(A.3) $VEH_{yj} = VEH_{y-1\ j-1} \times JUNK_j$ (general case)

$y \neq byr, \ j \neq 1$

where VEH_{yj} = number of vehicles that will be of age j at the end of year y

REG_y = number of new car registrations in year y (for past years $y \leq byr$)

Note: The first year of the simulation horizon, byr, is 1975 in our test runs and the old car stock includes vintages early as 1955. Both of these years are variables in MATHAIR. For example, the user could specify the simulation horizon to begin in byr = 1980.

$JUNK_j$ = 1 - scrappage rate of vehicles of age j

GROW = presumed annual growth rate of new car registrations after base year

TRANSPORTATION MODULE

Model Type and Capabilities

MATHEMATICA's transportation demand module is a disaggregated behavioral model based on the work of Domencich and McFadden. The module provides the following outputs:

- Mode-choice probabilities
- Trip-frequency probabilities
- Joint travel demand probabilities
- Number and composite price of auto, bus, and rail passenger trips
- Auto, bus, and rail passenger miles
- Auto, bus, and rail vehicle miles of travel (VMT)

All outputs are calculated for three travel modes, three trip purposes, and four spatial trip patterns.

Module Logic

The decision tree in Figure B-1 is the individual's travel decision process assumed by the Transportation Module. It corresponds to the following sequence of choices:

- The purpose of the trip is identified: work, shop, or other purpose.
- Auto, bus, or rail is chosen by the decision-maker after evaluating the relative cost and performance of each alternative.
- The probability of making or not making the trip (trip frequency) is determined as a function of the trip purpose and of the specific cost of travel by the preferred mode.
- Trip time of day, while not explicitly identified in the model, is a function of the purpose of the trip. Work trips are assumed to take place during peak-hour (high vehicle occupancy). Shopping and other-purpose trips are assumed to be undertaken at other times of the day.

In the model of Domencich and McFadden, trip frequency is determined before mode choice.

A flow chart of the Transportation Module used in MATHAIR is shown in Figure B-2.

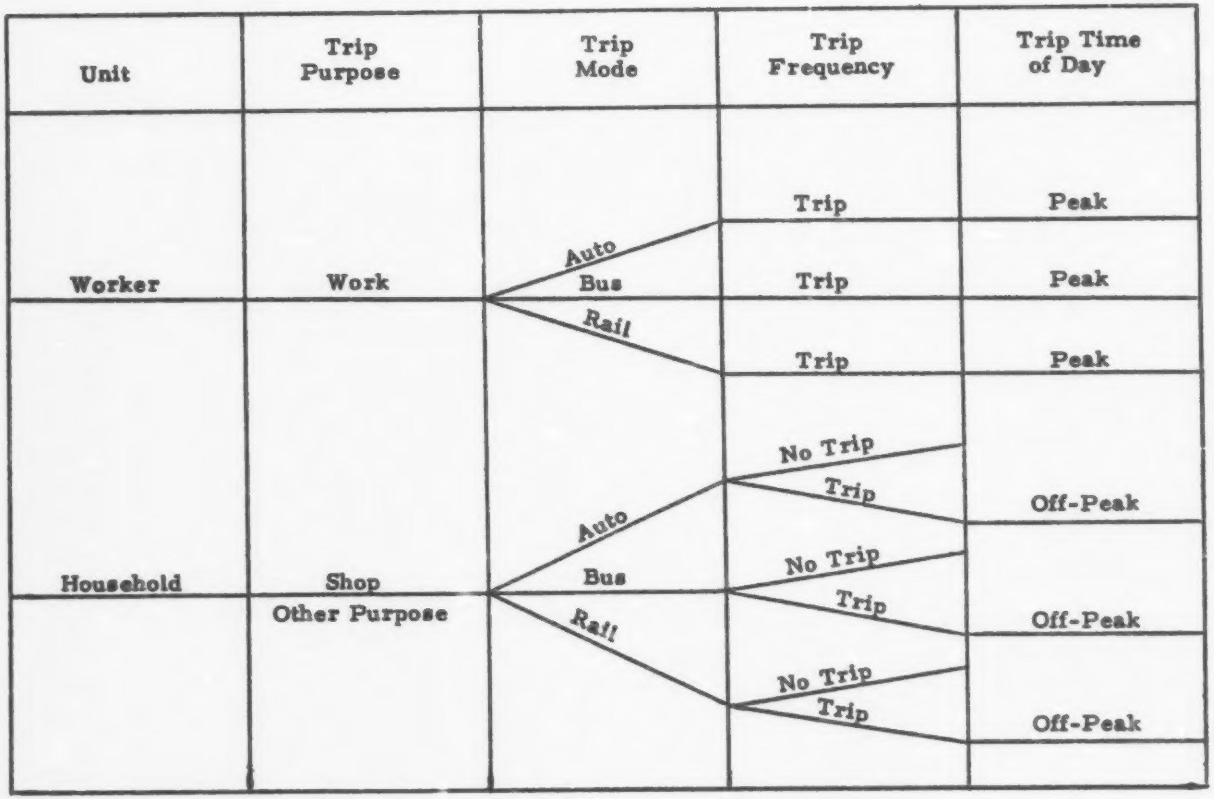

Figure B-1. Decision tree for transportation demand.

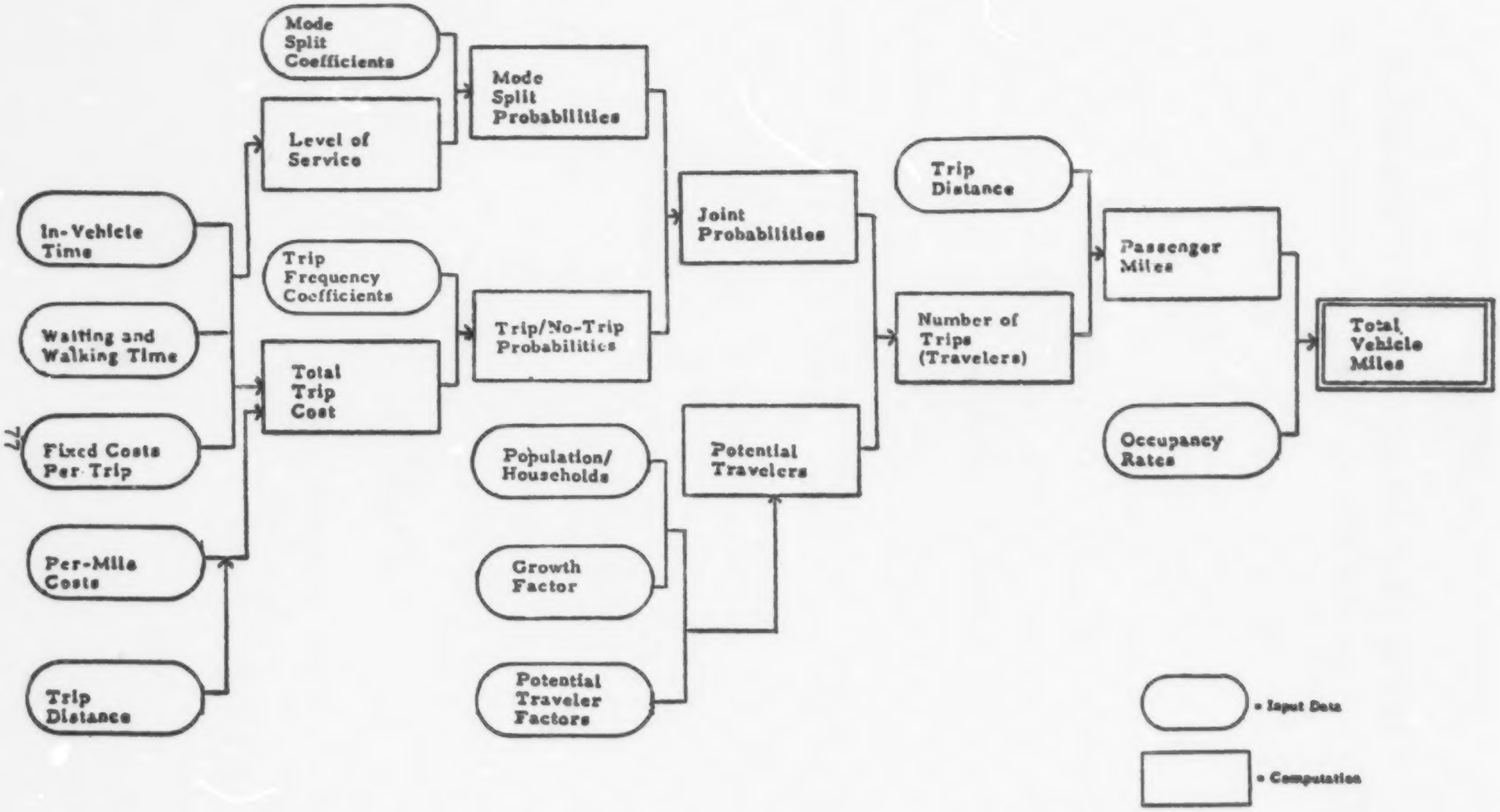

Figure B-2. Flowchart of the Transportation Module.

Definition of Variables and Major Equations in Transportation Module

AC^{j} = Automobile parking charges and operating costs (in dollars).

AIV^{j} = Automobile in-vehicle time (in minutes) by purpose.

AO^{ij} = Average vehicle occupancy for travel by i^{th} mode for j^{th} purpose.

ATD^{ij} = Average trip distance by i^{th} mode for j^{th} purpose.

AVOTR = Average value of time riding.

AVOTW = Average value of time waiting and walking.

$FARE^{ij}$ = The fare by i^{th} mode for j^{th} purpose.

H^{Aj} = Probability an individual will choose the automobile for a trip of purpose j rather than the bus.

$H^{A'j}$ = Probability an individual will choose the automobile for a trip of purpose j rather than the train.

H^{Bj} = Probability an individual will choose the bus for a trip of purpose j rather than the automobile mode ($H^{Bj} = 1 - H^{A'j}$).

HF = Probability an individual will make a trip.

H^{Tij} = Probability an individual will choose the train for a trip of purpose j rather than the automobile ($H^{Tj} = 1 - H^{A'j}$).

NT^{ij} = Number of trips by i^{th} mode for j^{th} purpose.

P^{ij} = Joint possibility of taking a trip by i^{th} mode for j^{th} purpose.

$\hat{P}^{ij}$ = The price of travel for the average trip by i^{th} mode and j^{th} purpose.

TSS^{ij} = Transit station to station time (in minutes) plus wait time by mode and purpose.

TW^{ij} = Transit walk time (in minutes) for the i^{th} mode and the j^{th} purpose.

UT^{j} = Potential number of trips for j^{th} purpose.

VMT^{ij} = Vehicle miles traveled by i^{th} mode for j^{th} purpose.

Modal Split--

- **Automobile-Bus Modal Split**

$$\log \frac{H^{Aj}}{1-H^{Aj}} = \log \frac{H^{Aj}}{H^{Bj}} = \alpha_0 + \alpha_1 TW^{Bj} + \alpha_2 (AIV^j - TSS^{Bj}) + \alpha_3 (AC^j - FARE^{Bj}) \tag{A.4}$$

- **Automobile-Train Modal Split**

$$\log \frac{H^{A'j}}{1-H^{A'j}} = \log \frac{H^{A'j}}{H^{Tj}} = \alpha_0 + \alpha_1 TW^{Tj} + \alpha_2 (AIV^j - TSS^{Tj}) + \alpha_3 (AC^j - FARE^{Tj} \tag{A.5}$$

- **Normalized Modal Split Probabilities**

$$W^{ij} = \frac{H^{ij}}{H^{Aj}+H^{Bj}+H^{Tj}} \tag{A.6}$$

i = trip mode
j = trip purpose

- **Trip Frequency**

$$\log \frac{HF}{1-HF} = \zeta_0 + \zeta_1 \hat{P}^{ij} \tag{A.7}$$

i = Trip mode
j = Trip purpose

- **Mode Specific Cost Equations**
  - **Auto Trip Cost**

$$\hat{P}^{Aj} = \left(AIV^j \times AVOTR\right) + AC^j \tag{A.8}$$

  - **Bus Trip Cost**

$$\hat{P}^{Bj} = \left(TW^{Bj} \times AVOTW\right) + \left(TSS^{Bj} \times AVOTR\right) + FARE^{Bj} \tag{A.9}$$

  - **Rail Trip Cost**

$$\hat{P}^{Rj} = \left(TW^{Tj} \times AVOTW\right) + \left(TSS^{Tj} \times AVOTR\right) + FARE^{Tj} \tag{A.10}$$

Joint Probabilities--

(A.11) $P^{ij} = (H^{ij}) \times (W^{ij})$

i = trip mode
j = trip purpose

where H^{ij} is assumed equal to one for work trips.

Transportation Module Outputs--

- Number of Trips Per Day

(A.12) $NT^{ij} = UT^{j} \times P^{ij}$

i = trip mode
j = trip purpose

- Passenger Miles Traveled Per Day

(A.13) $PMT^{ij} = NT^{ij} \times ATD^{ij}$

i = trip mode
j = trip purpose

- Vehicle Miles Traveled Per Day

(A.14) $$VMT_{ij} = \frac{PMT^{ij}}{AO^{ij}}$$

EMISSIONS MODULE

Automobile Emissions

The following equations are used to calculate automobile emissions. First it is necessary to calculate the number of miles driven by automobiles of each age:

(A.15) $$AMILE_{yj} = VMT_{y1} \times VEH_{yj} \times MILE_{j} \Big/ \left[\sum_{a} VEH_{ya} \times MILE_{a}\right]$$

where $AMILE_{yj}$ = average daily mileage driven by automobiles of age j in year y

VMT_{y1} = automobile vehicle miles traveled/day (VMT_{y2} is bus vehicle miles traveled (VMT))

$MILE_{j}$ = average daily miles presently driven by an automobile of age j (exogenous)

$\sum_{a}$ = summation is over all ages in stock

Automobile VMT, needed in the above equation, may be provided exogenously or else generated as an endogenous variable by the Transportation Module.

Emissions are then calculated as follows:

$$\text{(A. 16)} \quad E_{i,\text{poll}} = \sum_{\text{age}} \left[CC_{\text{poll}} \times C_{\text{poll, vint}} \times D_{\text{poll, vint, age}} \times SC_{\text{speed, poll}} \times \text{AMILE}_{i,\text{age}} \right] \times \frac{1}{907,185}$$

$$\text{(A. 17)} \quad CC_{\text{poll}} = \prod_{d} \left[(1 - P_{d,i,\text{age}}) + P_{d,i,\text{age}} \times (1 - R_{d}, \text{poll, age}) \right]$$

$$= \prod_{d} (1 - P_{d,i,\text{age}} \times R_{d,\text{poll, age}})$$

where $E_{i,\text{poll}}$ = emissions in tons/day of pollutant poll in year i

CC_{poll} = improvement factor due to devices

$C_{\text{poll, vint}}$ = emissions in grams/mi. of pollutant poll, from average unmodified automobile of vintage vint

$D_{\text{poll, vint, age}}$ = deterioration factor (1.0) as automobile ages

$SC_{\text{speed, poll}}$ = speed correction factor (corrects for difference between actual speed and speed at which standard emission measurements were made)

$\text{AMILE}_{i,\text{age}}$ = average daily mileage in year i by automobile of given age.

$\frac{1}{907,185}$ = conversion from grams to tons

$P_{d,i,\text{age}}$ = proportion of automobiles of given age (vintage) on which device d is installed in year i

$R_{d, poll, age}$ = proportion of emission of pollutant poll held back when device d is installed in automobile of given age.

Stationary Source Emissions

The following equations describe the calculation of stationary source emissions:

$$(A.18)\quad S_{i, poll} = \sum_{s \in S} SE_{s, i, poll}$$

$$(A.19)\quad SE_{s, i, poll} = SS_{s, poll} \times \prod_{d} \left[1 - (P_{sd} \times SDEV_{d, poll})\right]$$

where $S_{i, poll}$ = total stationary source emissions in year i for pollutant poll in tons/day

S = set of all stationary sources

$SE_{s, i, poll}$ = total daily emissions of pollutant poll in year i from source s

$SS_{s, poll}$ = emissions of pollutant poll from source s in tons/day

$\prod_{d}$ = product over all devices installed

AIR QUALITY MODULE

The following equations describe the Air Quality Module:

$$(A.20)\quad C_{i, CO} = \alpha_1 S_{i, CO} + \beta_1 M_{i, CO}$$

$$(A.21)\quad C_{i, NO_x} = \alpha_2 S_{i, NO_x} + \beta_2 M_{i, NO_x}$$

$$(A.22)\quad C_{i, OX} = \alpha_3 S_{i, HC} + \beta_3 M_{i, HC}$$

$$(A.23)\quad C_{i, SO_x} = \alpha_4 S_{i, SO_x} + \beta_4 M_{i, SO_x}$$

$$(A.24)\quad C_{i, Pb} = \alpha_5 S_{i, Pb} + \beta_5 M_{i, Pb}$$

where $C_{i, poll}$ = concentration of pollutant poll in year i

$S_{i, poll}$ = daily emissions of pollutant poll in year i from stationary sources

$M_{i, poll}$ = daily emissions of pollutant poll in year i from mobile sources

α_j = city-specific stationary source rollback coefficients*

β_j = city-specific mobile source rollback coefficients*

BENEFITS MODULE

MATHAIR's module for calculating the economic costs of air pollution damage can be bypassed if the user wishes to provide his own benefits module.

The MATHAIR Benefits Module allows the user to specify up to eight benefits categories ($i = 1, \ldots, 8$) for each of the five pollutants ($j = 1, \ldots, 5$) or forty benefit/pollutant categories. For each, the following information is required:

(i) dollar value of damages plus damage avoidance costs in some base year (D_{ij})

(ii) level of pollutant concentration producing baseline damage and damage avoidance costs (C_j)

(iii) rate at which damage (cost) will grow if pollutant level remains constant (r_i)

(iv) exponent for pollution concentration in damage function (γ_{ij})

(v) threshold below which no damage occurs (T_{ij})

The damage function is assumed to be of the following form, where the coefficients δ_{ij} are computed by MATHAIR from the baseline conditions:

$$\text{(A.25)} \quad D_{ij} = \delta_{ij} (C_j - T_{ij})^{\gamma_{ij}}$$

---

*α_j and β_j are calibrated (outside of MATHAIR) from base year estimated emissions and measured concentrations and then input to MATHAIR. Values for α and β are discussed in Appendix D.

If the concentration of pollutant j is E_j in year byr + k, then damages in that year (discounted to year byr) will be equal to

$$\delta_{ij}(E_j - T_{ij})^{\gamma_{ij}} \times (1 + r_i)^k \qquad \text{if} \qquad E_j \geq T_{ij}$$

$$0 \qquad\qquad\qquad \text{otherwise}$$

When a strategy is simulated, the Benefits Module computes the resulting damage and damage avoidance costs. Benefits due to a strategy can be calculated by subtracting associated costs from those produced in the baseline case.

COST MODULE

Automobile Device Costs

MATHAIR requires both input data and strategy information concerning air pollution control devices for automobiles. The input data describe emission reduction characteristics, expected device life, and device costs. Strategy information describes which devices should be installed, on which automobiles, and in what years.

The annual cost of increased fuel consumption and increased maintenance and the installed cost of the device are calculated by the Cost Module as follows:

$$\text{(A.26)} \quad COST_{i,\,fuel} = DCOST_{k,\,fuel} \times VEH_{ij} \times P_{kij} \; (1+R)^{i-byr}$$

where byr = base year

i = a year between the year of installation and the year of removal

$COST_{i,\,fuel}$ = the incremental fuel cost in year i of having installed device k in autos of age j

$DCOST_{k,\,fuel}$ = the annual unit increase in fuel cost for device k

VEH_{ij} = the number of autos of age j in year i

P_{kij} = the proportion of autos of age j in year i on which device k has been installed

R = the discount rate

The calculations are analagous for the maintenance costs associated with a control device.*

If the device is installed in year i and either it is removed before the simulation terminates, or the device has been on for the whole of its economic life when the simulation terminates, the entire cost is attributed to the simulation period. If neither of these conditions is met, only part of the cost is attributed to the simulation period. In either case, the annualized cost in year i is calculated as follows:

$$\text{(A.27)}\quad COST_{i,\,dev} = \sum_{y=i}^{t} \left[A_k / (1+R)^{y-byr} \right] \times VEH_{ij} \times P_{kij}$$

where t = the last year simulated

A_k = the annualized device cost

$$\text{such that } DCOST_{k,\,dev} = A_k + \frac{A_k}{1+R} + \ldots + \frac{A_k}{(1+R)^{(L-1)}}$$

where L = the maximum assumed device life or the number of years of use before the device is removed, whichever is less

$DCOST_{k,\,dev}$ = the purchase price of the k^{th} device

and the other variables are as defined above.

Stationary Source Device Costs

MATHAIR requires both input data and strategy information concerning air pollution control of stationary sources. Input data include an inventory of the stationary sources in each study region and device descriptions (emission reduction characteristics, device lifetime, device costs). Strategy information describes which devices should be installed, on which sources, and in which years.

The cost equations are analagous to those already described for automobile devices. Annual costs should reflect the economic value, if any, of the recovered pollutant.

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* Changes in the cost of fuel, due to the effects of control devices on gasoline consumption, are thus calculated as an annual cost per automobile although they are incurred on a per mile basis. Strategies restricting the use of the automobile do not affect the size of the stock but do reduce the number of miles driven. In these cases, the gasoline costs are currently adjusted manually after the model is run.

Other Costs

The cost of reduced (or enhanced) traveler mobility is manually calculated by the model user, using the method described in Appendix E.*

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* The current version of MATHAIR also calculates the costs of new buses required to meet any increase in demand for bus trips. Since we assume fares will cover these costs, they have been manually netted out of the costs presented in this report.

APPENDIX C

FORECASTING AGGREGATE DEMAND WITH A DISAGGREGATED TRANSPORTATION MODEL*

The disaggregated behavioral transportation model is estimated with observations of individual travel behavior and is intended to provide a basis for forecasting individual transportation demand probabilities. This type of model can also be used to predict aggregate demand.

The probability of the jth individual's demanding an auto trip rather than a bus trip, for example, can be expressed as

$$P_j = f(X_1^j, \ldots X_n^j) = \frac{e^{\sum_i \alpha_i X_i^j}}{1 + e^{\sum_i \alpha_i X_i^j}}$$

where the parameters $(\alpha_i, i = 1, \ldots, n)$ are assumed to be constant among individuals, but the probabilities (P_j) and differential level of service attributes $(X_i^j, i = 1, \ldots, n)$ are assumed to vary among individuals. If these individual functions are added over all N persons in the population and then both members of the equation are divided by N, we get

$$\overline{P} = \frac{1}{N}\sum_{j=1}^{N} P_j = \frac{1}{N}\sum_{j=1}^{N} f(X_1^j, \ldots, X_n^j)$$

where $\overline{P}$ is the average probability for the population. In the very special case where f is linear, then

$$\overline{P} = f(\overline{X}_1, \ldots, \overline{X}_n),$$

---

* Based on the discussion in D. McFadden and F. Reid, Aggregate Travel Demand Forecasting from Disaggregated Behavioral Models, presented at Fifty-fourth Annual Meeting of the Transportation Research Board, Washington, D. C. (January 1975).

and f is easily aggregated, with the average probability being equal to the same function f of the average of the variables. Analytic aggregation may be feasible even if f is not linear.

The function f specified above is derived from assumptions about the individual's utility function. In the disaggregate behavioral model described by Domencich and McFadden, the utility function is assumed to contain a stochastic element to reflect the individual's idiosyncracies in taste or unobserved variations in the observed attribute vector $X = \{X_1, \ldots, X_n\}$. Assuming that the non-stochastic part of the utility function is linear in the attributes, McFadden and Reid have investigated the special case where the stochastic elements in the individual utility function upon which the probability expressions are based is standard normal (the probit model). In this case, a simple closed formula can be obtained for the aggregate probability (using matrix notation):

$$P_j = \Phi(a' X^j)$$

where P_j is the probability of response (i.e., choice of particular mode) by jth individual.

Φ is cumulative normal density.

a is the vector of estimated weights

X^j is the vector of differential impedance between modes for the jth individual

X is assumed normal with mean $\overline{X}$ and covariance matrix A.

If we let $\sigma^2 = a'Aa$, then McFadden and Reid show that

$$\overline{P} = \Phi\left(\frac{a'\overline{X}}{\sqrt{1 + \sigma^2}}\right)$$

In other words, the aggregate prediction obtained from using aggregate data in the disaggregated model should be attenuated by a factor reflecting the degree of heterogeneity of the variables facing the individuals. If the area is homogeneous, then $\sigma^2 = 0$ and the disaggregate model can be used without correction factor for aggregate prediction.

The model used in this study is not a probit model, but a conditional logit model, estimated by McFadden, in which the stochastic elements are assumed to have a Weibull distribution. While McFadden makes this assumption for computational facility within the disaggregate framework, it does not lead to a simple closed formula for aggregate prediction.

In this study we have implicitly assumed that zones are homogeneous by making aggregate predictions with the disaggregated model. According to McFadden and Reid, the nature of the bias with any sigmoid-shaped choice function (and thus with any cumulative density function) is toward the extreme possible values: too low for values below 0.5, too high high above 0.5 -- that is, the assumption of homogeneity for a zone that is in fact heterogeneous means that demand elasticities will be over-estimated.

Since we recalibrate the constant terms (in all choice functions) to ensure proper base-year predictions, the bias in our model enters when we simulate policy change without calculating (or estimating) accompanying change in the covariance matrix. As McFadden and Reid state:

> We note that specifying the precise effect of a policy change on A [the covariance matrix A] may be challenging; various approximations may become necessary, including the extreme approximation ... that A is always zero and is therefore unchanged by policy.

This difficulty is present even in the case of the probit model where an analytic expression exists for the aggregate function. Given our use of the logit model and the absence of such an analytic expression, we are obliged to accept the error introduced by this approximation -- an over-estimation of responsiveness to policy change.

APPENDIX D

DISPERSION PROPERTIES OF MOBILE SOURCE AND STATIONARY SOURCE EMISSIONS

This somewhat technical appendix draws on material from D. Bruce Turner's Workbook of Atmospheric Dispersion Estimates. * The purpose of the appendix is to display the results of some calculations comparing the dispersion properties of non-reactive air pollutants from stationary and from mobile sources. The results make it possible to compare the cost-effectiveness of pollution control strategies for the two kinds of sources. If we assume that the ambient concentration of a pollutant is linear in emissions and is equal to α times mobile source emissions plus β times stationary source emissions, then we can show that the ratio α/β ranges over several orders of magnitude. The value of the ratio depends on such variables as climatic stability, wind direction, and distance from the source. If a single value must be chosen, we propose 100 based on preliminary calculations reported in this appendix.

Mobile and stationary sources differ in two essential respects: height of emission and spatial aggregation. Mobile sources have an emission height of at most a few meters; stationary sources have a height of up to 200-300 meters. Furthermore, a given quantity of pollutant emitted from a single stationary source is obviously more concentrated than the same total quantity emitted from several mobile sources. We will now examine the consequences of these differences.

CONSEQUENCES OF STACK HEIGHT

The height of emissions (H) is the height of the plume centerline when it becomes essentially level. In what follows, we will assume that H = 10 meters for mobile source and H = 100 meters for stationary sources. We assume that the plume has a Gaussian distribution in both the horizontal and vertical planes and that there is no deposition or reaction at the surface. We originate a coordinate system at the base of the stack and are interested in calculating concentration (g/m^3) at (x, y, z,) where the x-axis is parallel to the wind direction. The system is illustrated in Figure D-1.

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*D. Bruce Turner, Workbook of Atmospheric Dispersion Estimates, U. S. Department of Health, Education and Welfare (1969).

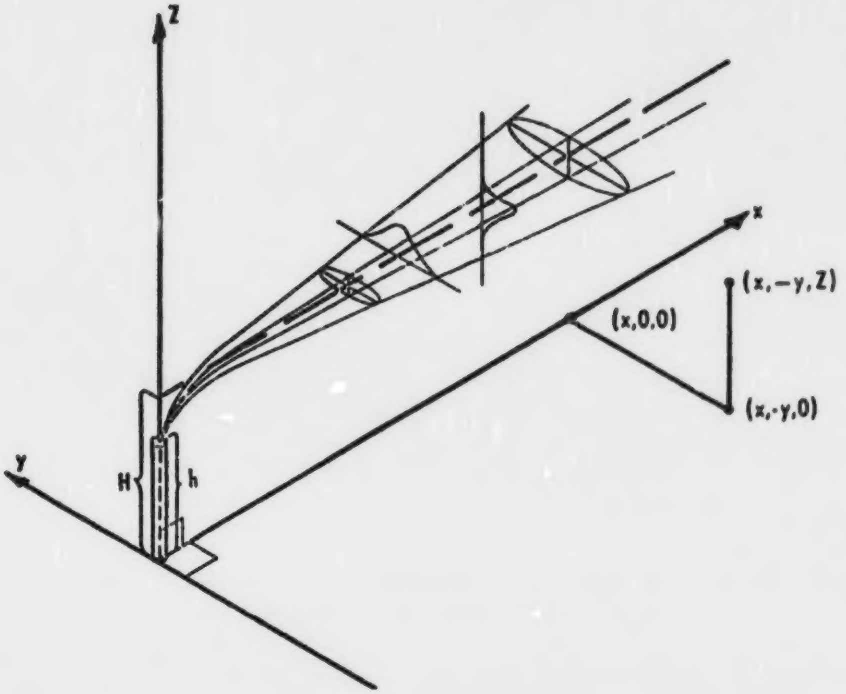


Figure D-1. Coordinate system showing Gaussian distributions in the horizontal and vertical.

Source: D. Turner, op. cit.

When temperature decreases with height at a rate greater than 5.4° per 1,000 feet (1°C per 100 meters), the atmosphere is in unstable equilibrium (and vertical motions are enhanced). When temperature decreases at a lower rate or increases with height (inversion), vertical motions are damped or reduced and equilibrium is stable. Stability categories can be designated on the basis of surface wind speed and amount of incoming solar radiation (day) or cloud cover (night) illustrated in Figure D-2. The categories range from A (unstable) through F (stable), and D is considered the neutral class.

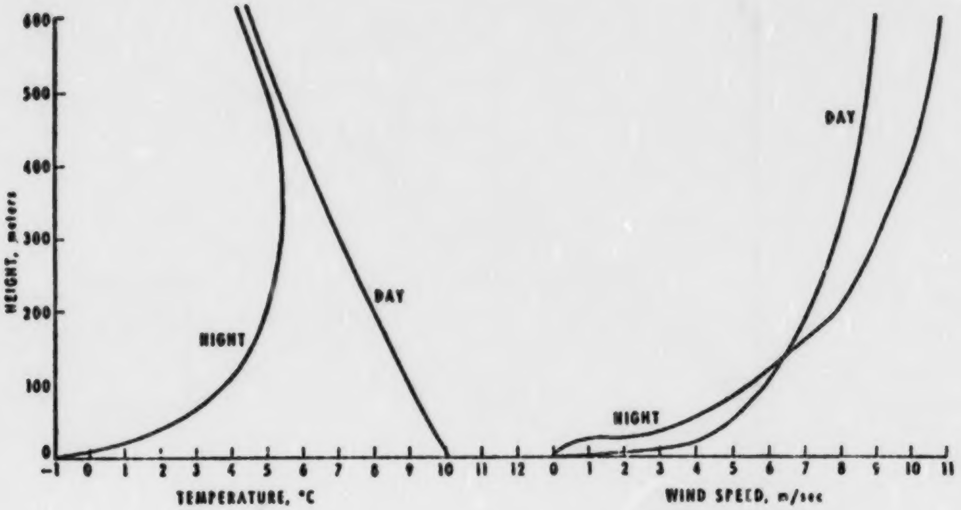


Figure D-2. Examples of variation of temperature and wind speed with height (after Smith, 1963).

Source: D. Turner, op. cit.

GROUND LEVEL CONCENTRATION DOWNWIND

In the Workbook of Atmospheric Dispersion Estimates, Turner plots relative ground-level (i. e., z = 0), downwind (i. e., y = 0' concentrations times windspeed ($\chi u/Q$, where χ is concentration, u is windspeed, Q is emission) against distance (i. e., for x = .1 to 100 kilometers), at various heights of emission (H) and various limits to vertical mixing, for each stability class. We will fix the downward distance at one kilometer. Given that $\chi u/Q = Y$, then $\chi = YQ/u$. Comparing Y/u (or simply Y) for H = 10 meters and for H = 100 meters, under otherwise identical conditions, we find the following values on a neutral day:

	H = 10	H = 100
Y	$\sim 10^{-4}$	$\sim 10^{-6}$

Given the assumptions we have made, the multiplier for mobile sources (α) is about 100 times greater than for stationary sources (β). The ratio ($\gamma = \alpha/\beta$) approaches infinity on stable days and approaches one on unstable days (at a distance of one kilometer).

An average value for γ would appear to be 100 considering emission height differences only. Because of the significant differences in actual patterns of spatial distribution, we will inspect γ when $y \neq 0$ (i.e., not directly downwind) and when $z \neq 0$ (i.e., at points higher than ground level).

CONCENTRATIONS ABOVE GROUND LEVEL

When $z > 0$ (i.e., above ground level), the following values of $Y = \chi u/Q$ pertain for emission heights of H = 10 and H = 100 meters:

	H = 10	H = 100
z = 0 meters	-10^{-4}	-10^{-6}
10 meters	-10^{-4}	-10^{-6}
50 meters	$-.5 \times 10^{-4}$	$-.2 \times 10^{-4}$
100 meters	-10^{-6}	-7×10^{-4}

These calculations show that the ground level emission characteristics are reasonable estimates for at least the first thirty feet of the atmosphere.

GROUND LEVEL CONCENTRATIONS OTHER THAN DOWNWIND

When $y \neq 0$ (i.e., not directly downwind), $\chi u/Q$ must be multiplied by a factor of $K = e^{-1/2\,(y/\sigma y)^2}$, where σy is the standard deviation of plume concentration distribution in the horizontal direction. We find the following values for K for a stability class D day when y = 1 kilometer:

	x = 1 kilometer	x = 10 kilometers
K	1.2×10^{-34}	.36

Thus, concentrations other than downwind are extremely sensitive to the location of the source of emissions.

These observations suggest the importance of the location of a fixed source with respect to the prevailing wind directions of a given urban area. Let us represent the urban area as a circle and the emission sources as in Figure D-3.

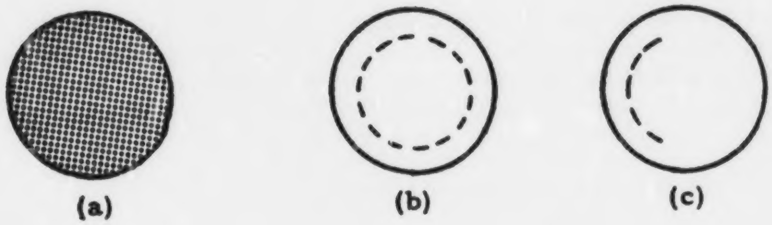

(a) (b) (c)

Figure D-3. Three possible distributions of emission sources.

In (a) the emissions are uniformly distributed on the surface of the area, as they might be idealized to represent mobile sources. In (b) the emissions are uniformly distributed around the perimeter, and in (c) around part of the perimeter. Both (b) and (c) are representative of stationary sources of air pollution. If total emissions are the same in all three cases, average concentration above the area will, in general, not be the same in all three cases depending, in particular, upon wind direction. Furthermore, the average differences in concentrations may span many orders of magnitude.

APPENDIX E

TRANSPORTATION COSTS AND BENEFITS: COMPUTING CONSUMERS' SURPLUS

The purpose of computing the consumers' surplus (CS) is to measure one aspect of the cost (or benefits) of a change in transportation policy: the cost to consumers of a strategy in terms of changed travel costs including the value of foregone (or induced) trips. We shall consider CS to be the maximum consumers are willing to pay for a decrease in the price (or the minimum they would accept as compensation for an increase in the price) of a given mode of travel.

In aggregating from the individual consumer to all consumers in the market, we are making the implicit assumption that the marginal social utility of income is the same for all consumers (i.e., that an additional dollar of income contributes an equal amount to social welfare regardless of who receives it). Furthermore, our model includes auto, bus and rail trips and no other commodities. This amounts to assuming that price changes in other sectors of the economy have an insignificant effect on the consumers' surplus we calculate.

CONCEPT OF CONSUMERS' SURPLUS

Let us illustrate the concept with an example. Suppose the cost of other travel modes remains unchanged and the cost of a bus trip is reduced from P_0 to P_1 as illustrated in Figure E-1.

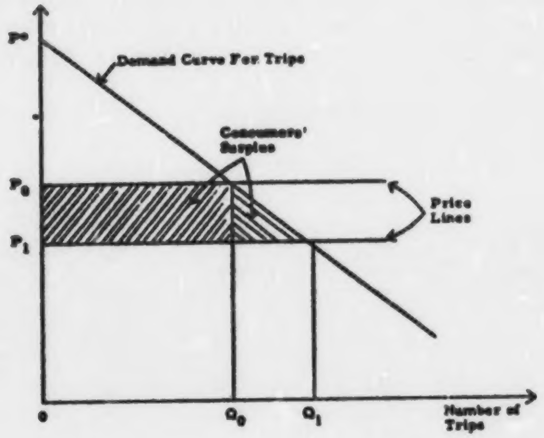


Figure E-1. Consumers' surplus.

The demand curve in Figure E-1 is the locus of points (here assumed linear) relating the quantity of trips taken (horizontal axis) to given trip prices (vertical axis). Initially Q_0 trips are taken at unit price P_0. When price is decreased to P_1. bus trip consumption is increased to Q_1.

The downward slope of the demand curve has two interpretations: (a) it reflects the fact that fewer people travel as trips become more expensive; and (b) it indicates that the value of a trip varies over members of the population; some are willing to pay more than the trip price (up to P*), while others are willing to pay only the trip price and no more. Moreover, as the difference between value (points on the demand curve) and prices (price lines P_0 and P_1, respectively) diminishes, more trips are demanded, up to a final demand level (Q_0 and Q_1, respectively).

Corresponding to interpretation (b), the triangular area between the demand curve and each price line measures the aggregate value of trips, above and beyond the money outlay required to purchase the number of trips demanded. The difference between these two areas is the CS shaded on Figure E-1.

Paralleling perspective (a) above, as the price of travel changes, inducing more or fewer trips, the area between demand curve and the price line will change, producing CS.

The shaded area represents the most consumers will pay to have the reduction in price. This consists of two parts: a rectangular portion corresponding to CS on the original Q_0 trips plus a triangular portion corresponding to CS on the $Q_1 - Q_0$ additional trips induced by the price change. (In the case of a price increase, the latter corresponds to a loss in CS due to foregone trips.)

THE CONSUMERS' SURPLUS MODEL

The CS model provides a methodology for calculating the value of CS for specified strategy changes as described in Figure E-2: Within the Transportation Module, demand curve parameters for all trip modes, patterns and purposes are accessible. These curves are constructed and the area bounded by each curve and the relevant price line is computed.

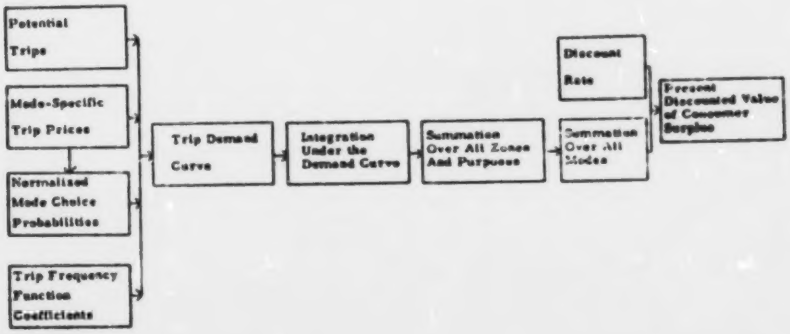

Potential Trips
Mode-Specific Trip Prices
Normalized Mode Choice Probabilities
Trip Frequency Function Coefficients
Trip Demand Curve
Integration Under the Demand Curve
Summation Over All Zones And Purposes
Summation Over All Modes
Discount Rate
Present Discounted Value of Consumer Surplus

Figure E-2. Flow chart of consumers' surplus model.

For each mode, the measured CS is summed over trip zonal patterns and over trip purposes. The summed modal CS values are further combined to yield total CS which is discounted to yield the present value of all benefits accruing in the future.

FORM OF THE DEMAND CURVE

The trip demand curves in the Transportation Module have the following form:

$$Q_{ijk} = UT_{ij} \times W_{ijk} \times HF_{ijk}$$

where i = zone.

j = purpose.

k = mode.

Q = quantity of trips demanded.

UT = number of potential travelers.

W = mode choice probability.

HF = trip frequency probability.

The term "price," as used in the transportation demand functions, includes both time and out-of-pocket costs incurred in securing transportation services. The time and money cost variables are multiplied by coefficients which estimate their relative impact on the total composition of trip prices perceived by travelers.

Cross-price terms are expressions containing prices for two or more transportation modes. These are essential to the initial determination of mode split. The mode-split probabilities (W_{ijk}) represent the substitutability between competing modes. Thus, cross-price terms enter into the final demand curve for each mode indirectly in the form of the mode-split probabilities.

Own-price expressions are equations containing only the time and money costs specific to the particular mode under study. Cross-price is affected by change in own-price.

The relationship between quantity and own-price is expressed by decomposing the members of the right-hand side of the equation which depend on price:

1) $$\log \frac{HF_{ijk}}{1 - HF_{ijk}} = \delta_0^j + \left(\delta_1^j \times P_{ijk}\right)$$

$$HF_{ijk} = \left(e^{\delta_0^j + \delta_1^j \times P_{ijk}}\right) \Big/ \left(1 + e^{\delta_0^j + \left(\delta_1^j \times P_{ijk}\right)}\right)$$

2) W_{ijk} is also affected by price by a relationship we will denote $W_{ijk} = W_{ijk}(P_{ijk})$.

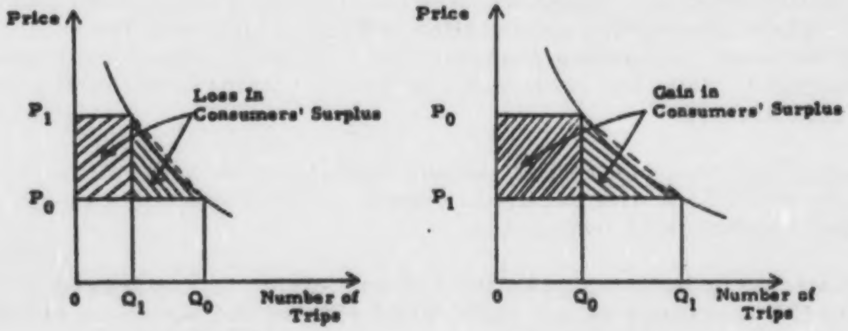
The final demand function can then be written

$$Q_{ijk} = UT_{ij} \times W_{ijk}(P_{ijk}) \times e^{\delta_0^j + \left(\delta_1^j \times P_{ijk}\right)} \Big/ \left(1 + e^{\delta_0^j + \left(\delta_1^j \times P_{ijk}\right)}\right)$$

CS in the case of price decrease is evaluated by the following integral:

$$CS_{ijk} = \int_{P_{ijk}^N}^{P_{ijk}^0} UT_{ij} \times W_{ijk}(P) \times HF_{ijk}(P)\, dP$$

This function is not readily integrable by analytic means, but we can approximate the change in CS by assuming that the demand function is a linear function of price over the relevant range. Graphically the change in CS for an increase in price of automobile trips and for a decrease in price of bus trips is approximated as shown in Figure E-3.



a. Increase in Price of Auto Trips

b. Decrease in Price of Bus Trips

Figure E-3. Approximation of consumers' surplus

In both cases the broken line is the linear approximation to the demand curve for prices between P_0 and P_1 .

TWO OR MORE SIMULTANEOUS PRICE CHANGES

When the prices of two (or more) substitutes change simultaneously, the accepted methodology is to consider the price changes one at a time sequentially (in any order) and to sum the corresponding consumers' surpluses. If we assume a simultaneous increase in the cost of automobile trips and decrease in the cost of bus trips, we will sum:

(i) The (loss of) CS due to the increase in automobile trip cost given the original bus trip cost, and

(ii) the CS due to the decrease in bus trip cost given the new automobile trip cost.

Furthermore, this will be the same as the sum of:

(iii) The CS due to the decrease in bus trip cost given the original automobile trip cost, and

(iv) the (loss of) CS due to the increase in automobile trip cost given the new bus trip cost.

This equality will hold provided the income effect is small, where income effect is the product of the following two terms: proportion of income spent on transportation and income elasticity of transportation demand. The approximation to CS in the case of two simultaneous price changes (i.e., increase in price of automobile trips and simultaneous decrease in price of bus trips) is calculated as follows.

First we calculate the approximation of the two quantities indicated as (i) and (ii) above. The first quantity, (i), is calculated as in the case of a single price change: increase in the price of an automobile trip. The second quantity, (ii), however, has to be calculated with respect to the new demand curve for bus trips which shifts outward (from D_0D_0' to D_1D_1' in Figure E-4) as a result of the increased price of automobile trips. The figure indicates the quantity of bus trips originally demanded (Q_0), the quantity demanded at the original price of a bus trip after the increase in automobile price (Q'), and the quantity demanded after the decrease in bus price (Q_1). The resulting gain in consumer surplus to bus trip takers is the triangle indicated on Figure E-4.

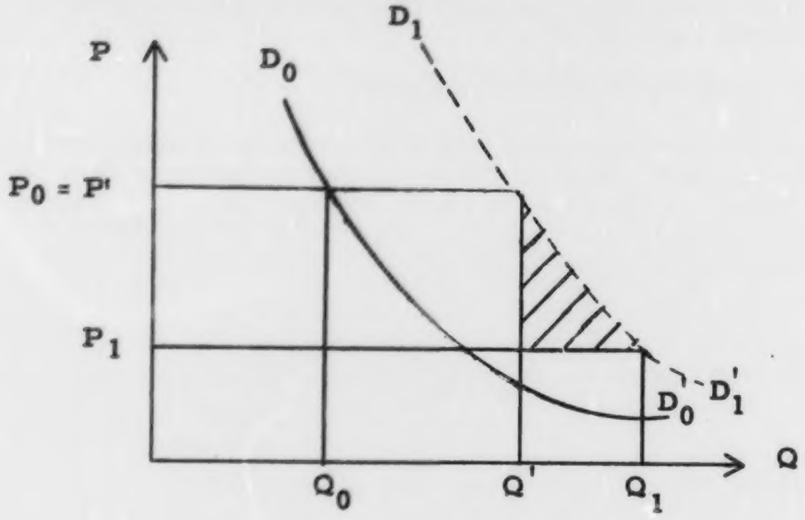


Figure E-4. Gain in consumers' surplus corresponding to (ii).

The analagous calculation is made in the second case indicated as (iii) and (iv). The loss in automobile consumers' surplus corresponding to (iv) is the triangle indicated in Figure E-5.

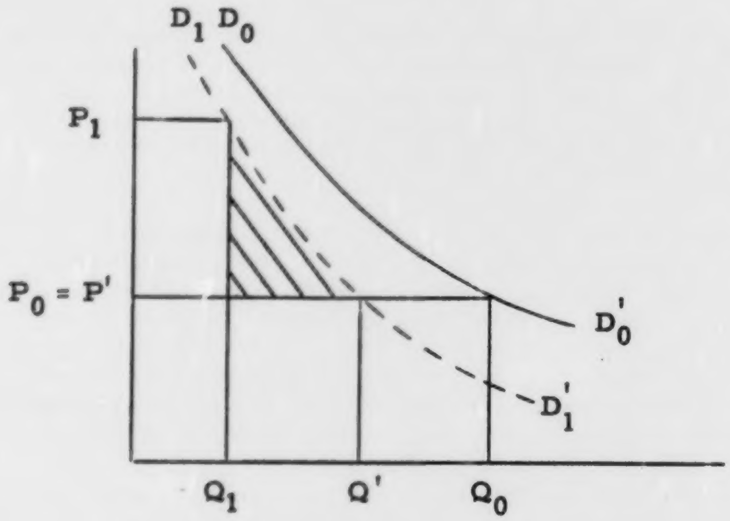


Figure E-5. Loss in consumers' surplus corresponding to (iv).

The linear approximation to the shifted demand curve is not shown in Figures E-4 and E-5 to facilitate the exposition.

Under some measures to reduce automobile attractiveness or increase the attractiveness of mass transportation, the cost of reduced mobility or benefit of enhanced mobility is less than the full decrement or increment to CS. For example, if automobile costs are increased via a tax, the public treasury will collect additional taxes in the amount of the tax rate times the amount of taxed activity remaining after the imposition of the tax. These collected taxes represent a transfer, and should be netted out of calculated CS loss. In like manner, reduction of bus fares will require an increase in the operating subsidy required for bus service. This also represents a transfer, and should be netted out of any calculated increase in CS stemming from a reduction in bus fares. Figure E-6 shows the same demand curves as Figure E-3 with transfer payments indicated.

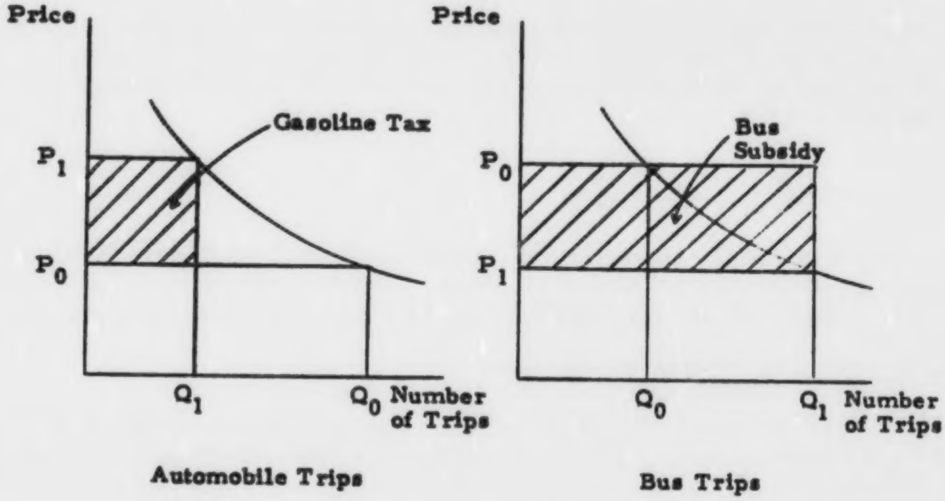


Figure E-6. Transfer payments.

CS used in the calculations presented in this report is the average of (i) plus (ii) and (iii) plus (iv) net of transfer payments.

APPENDIX F

INPUT DATA

This appendix describes the input data required for the MATHAIR model. Where appropriate, data are presented for each of the four regions (Los Angeles, New York, Washington and Chicago) used for policy simulation studies.

AUTOMOBILE STOCK MODULE INPUTS

The Automobile Stock Module takes three inputs: new automobile registrations for 1955-75, shown in Table F-1; scrappage rates, given in Table F-2; and annual growth rate for new automobile registrations, assumed to be 2 percent.

TRANSPORTATION MODULE INPUTS

A flowchart of the Transportation Module is shown in Figure F-1. Module inputs, including parameter estimates, represented on the flowchart have been numbered on this figure and are presented in this appendix.

Trip Costs, Times, and Distances (Boxes 1-5)

We have assumed that the length of any trip for a given purpose is independent of the mode choice, and have used estimates based on automobile distances. Average bus speeds (and rail transit speeds for New York and Chicago) have been obtained from a variety of sources including detailed city-specific published reports such as the Metropolitan Washington Council of Governments report on Existing Transportation Systems in the Washington Metropolitan Area, less detailed general reports such as the MVMA Urban Transportation Factbook, and in some cases from conversations with transit company officials. Speeds, waiting times and walking times were estimated. Fares were derived from published schedules and conversations with transit company officials. Table F-3 shows a sample calculation of automobile parking costs; Table F-4 shows typical automobile round-trip distances, speeds and in-vehicle times. The following ten tables (Tables F-5 through F-14) show the Transportation Module inputs corresponding to boxes 1 through 5 of Figure F-1 for the four study regions.*

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* Value of time, a cost component not shown here, is derived from the mode-split parameters and is presented in the next section.

TABLE F-1. NEW AUTOMOBILE REGISTRATIONS, 1955-1975

(in thousands)

Year	Los Angeles	New York	Washington, D. C.	Chicago
1975	520	780	260	470
1974	510	770	250	460
1973	500	770	216	457
1972	513	730	165	464
1971	451	690	162	403
1970	476	720	169	382
1969	561	760	164	409
1968	562	830	178	420
1967	601	820	205	445
1966	855	1160	186	584
1965	1170	1470	200	703
1964	601	820	205	445
1963	541	738	185	401
1962	481	656	164	356
1961	391	533	133	289
1960	397	541	135	294
1959	649	886	221	481
1958	643	877	219	476
1957	517	705	176	383
1956	841	1148	287	623
1955	589	803	201	436

Source: Estimated using Motor Vehicle Manufacturers Association of the U. S., Inc., Automobile Facts and Figures (1972).

Note: The growth rate in new automobile registrations for 1975 through 1984 was assumed to be 2% for all urban areas.

TABLE F-2. AUTOMOBILE SCRAPPAGE RATE

Age of Automobile	Percent of Automobiles of Given Age Still in Stock
1	100.0
2	99.0
3	98.0
4	96.0
5	92.0
6	85.0
7	74.0
8	60.0
9	44.0
10	32.0
11	23.0
12	17.0
13	12.0
14	9.0
15	6.0
16	4.0
17	3.0
18	2.0
19	1.0
20	0.5

Source: Estimated using Motor Vehicle Manufacturers Association 1972 Automobile Facts and Figures, p. 30.

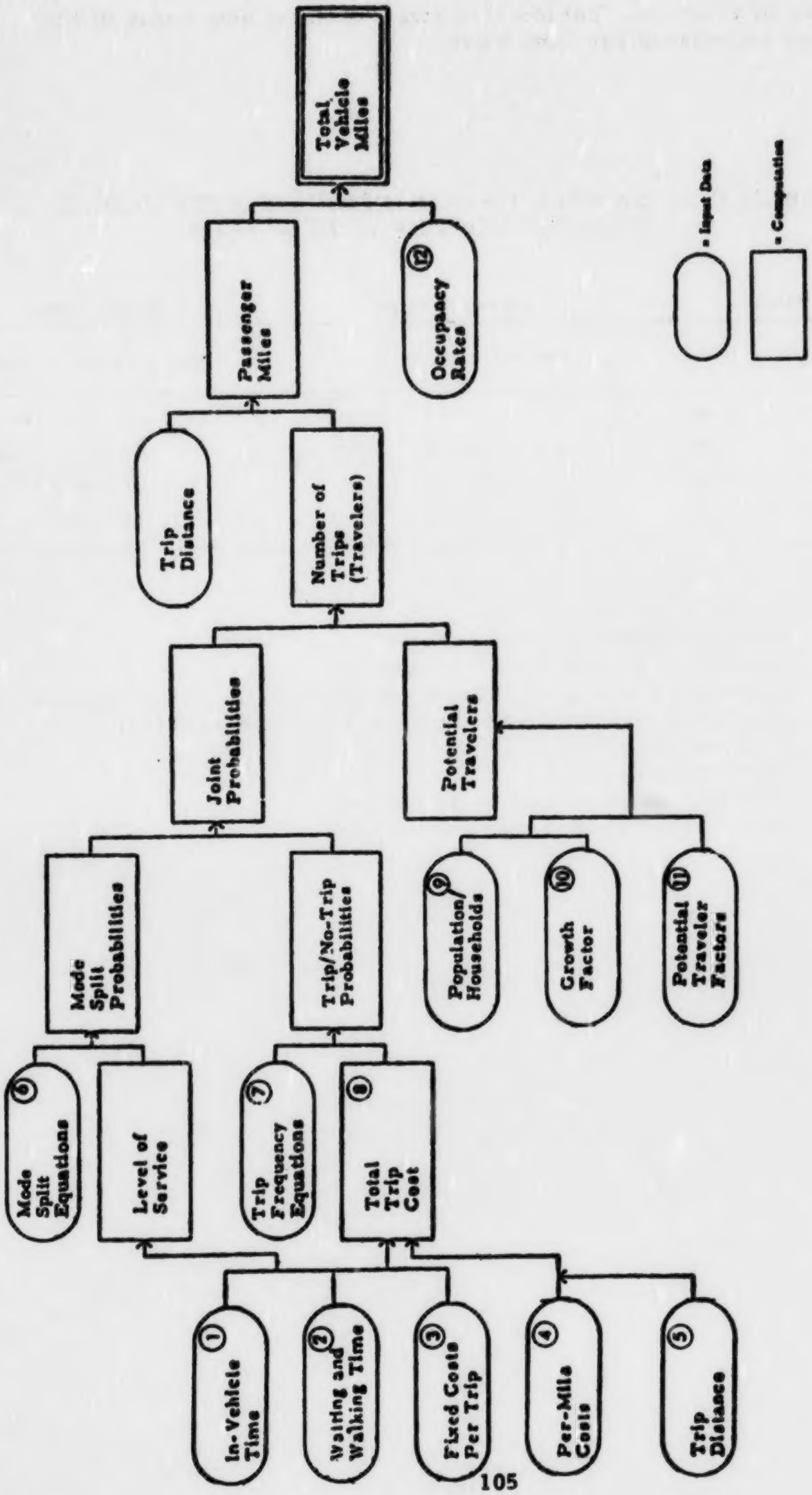

Figure F-1. Flowchart of the Transportation Module

By way of example, Tables F-3 and F-4 show how some of the variables were calculated for New York.

TABLE F-3. SAMPLE CALCULATION OF AUTOMOBILE PARKING COSTS FOR NEW YORK

	WORK TRIPS				SHOPPING TRIPS				OTHER TRIPS			
Origin/ Destination	Hrs.	x C	x PPP	= Total	Hrs.	x C	x PPP	= Total	Hrs.	x C	x PPP	= Total
C-C-C	8	0.30	50	$1.20	1	0.75	100	$0.75	1	.75	100	$0.75
S-S-S	8	0.10	25	0.20	1.5	0.20	50	0.15	1	.20	100	0.20
C-S-C	8	0.10	25	0.20	2	0.20	50	0.20	1	.20	100	0.20
S-C-S	8	0.30	50	1.20	2	0.75	65	0.975	1	.75	100	0.75

Source: Estimated

Notes:
Hrs. = average length at time parked
C = average cost per hour for parking
PPP = percentage of total parkers using paid spaces (as opposed to employer-provided and/or on-street free parking)
C-C-C = trips within center
S-S-S = trips within suburb
C-S-C = round-trips from center to suburb
S-C-S = round-trips from suburb to center

TABLE F-4. TYPICAL AUTOMOBILE ROUND-TRIP PATTERNS FOR NEW YORK

Purpose	Origin-Destination Nodes	Distance	Average Speed	In-Vehicle Time	Source
Work	C-C-C	11.2	17.0	39.5	Data for typical one-way trips were used to derive round trips. The average peak CBD speed of 21.6 mph reported in the SDC study was felt to be too high to reflect downtown congestion. It was adjusted downward 25% to 17 mph.
Work	S-S-S	11.2	21.6	31.1	Data from typical one-way trips taken from SDC Survey and doubled to derive suburb round-trip work trips.
Work	C-S-C	43.0	37.8	68.3	Data for typical long-distance work trip used to derive round-trips. Average speed increased 10% to reflect less congestion on morningcommuteout of CBD and evening trip into CBD.
Work	S-C-S	43.0	34.0	75.9	Data for typical long-distance (type B) work trip used directly to derive round trip data.
Shop	C-C-C	2.0	21.1	5.7	Data from typical shop trip used with CBD speed adjusted downward 15% to reflect downtown congestion. CBD shopping trips were also felt to be too long and were assumed to avg. 2.0 mi. round trip.
Shop	S-S-S	4.0	24.9	9.6	SDC Survey
Shop	C-S-C	20.0	39.7	30.2	Average C-S-C work trip speed increased 5% to reflect off-peak conditions.
Shop	S-C-S	20.0	35.7	33.6	Average S-C-S work trip speed increased by 5% to reflect off-peak conditions.
Other	C-C-C	20.6	21.1	58.6	Composite roundtrip of 20.6 miles assumed with average speeds equal to off-peak speeds assumed above for shopping trips.
Other	S-S-S	20.6	24.9	49.6	
Other	C-S-C	40.0	39.7	60.5	
Other	S-C-S	40.0	35.7	67.2	

Source: Estimated from Systems Development Corporation (SDC), A Survey of Average Driving Patterns in Six Urban Areas of the United States (1971), p. 40, and Motor Vehicle Manufacturers Association, 1972 Automobile Facts and Figures, p. 35.

C-C-C	trips within center
S-S-S	trips within suburb
C-S-C	round-trips from center to suburb
S-C-S	round-trips from suburb to center
CBD	central business district

TABLE F-5. AUTO TRAVEL DATA, LOS ANGELES

(Boxes 1-5 of Figure F-1)

Trip Type	Round Trip Distance (miles)	Average Speed (mph)	Total In-Vehicle Time (minutes)	Fixed Cost Per Trip	Variable Cost Per Mile
Work					
C-C-C	11.6	20.5	33.9	$ .05	$ 0.04
S-S-S	11.6	22.7	30.6	0	0.04
C-S-C	30.6	30.4	59.4	0	0.04
S-C-S	30.6	27.0	67.9	.05	0.04
Shop					
C-C-C	5.2	21.7	14.4	$ 0	$ 0.04
S-S-S	5.2	21.7	14.4	0	0.04
C-S-C	15.0	30.7	29.3	0	0.04
S-C-S	15.0	30.7	29.3	0	0.04
Other					
C-C-C	20.6=	22.3	55.4	$ 0	$ 0.04
S-S-S	20.6	22.3	55.4	0	0.04
C-S-C	30.0	30.7	58.6	0	0.04
S-C-S	30.0	30.7	58.6	0	0.04

C-C-C trips within center
S-S-S trips within suburb
C-S-C round-trips from center to suburb
S-C-S round-trips from suburb to center

TABLE F-6. BUS TRANSIT DATA, LOS ANGELES

(Boxes 1-5 of Figure F-1)

Trip Type	Round Trip Distance (miles)	Average Speed (mph)	Total In-Vehicle Time (minutes)	Round Trip Wait Time	Total Walk Time	Round Trip Fare
Work						
C-C-C	13.8	15	46.4	6	17.0	$ .60
S-S-S	13.8	16	43.5	8	16.0	.60
C-S-C	33.0	26	70.6	7	16.5	1.50
S-C-S	33.0	24	76.5	7	16.5	1.50
Shop						
C-C-C	4.0	18	17.3	13	17.0	$ .60
S-S-S	4.0	19	16.4	18	16.0	.60
C-S-C	15.0	30	30.0	15	16.5	.80
S-C-S	15.0	30	30.0	15	16.5	.80
Other						
C-C-C	20.6	18	68.6	13	17.0	$ .80
S-S-S	20.6	19	63.8	18	16.0	.80
C-S-C	30.0	30	60.0	15	16.5	1.50
S-C-S	30.0	30	60.0	15	16.5	1.50

C-C-C	trips within center	C-S-C	round-trips from center to suburb
S-S-S	trips within suburb	S-C-S	round-trips from suburb to center

TABLE F-7. AUTO TRAVEL DATA, NEW YORK
(Boxes 1-5 of Figure F-1)

Trip Type	Round Trip Distance (miles)	Average Speed (mph)	Total In-Vehicle Time (minutes)	Fixed Cost Per Trip	Variable Cost Per Mile
Work					
C-C-C	11.2	17.0	39.5	$1.20	$ 0.04
S-S-S	11.2	21.6	31.1	.20	0.04
C-S-C	43.0	37.8	68.3	.20	0.04
S-C-S	43.0	34.0	75.9	1.20	0.04
Shop					
C-C-C	2.0	21.1	5.7	$ .75	$ 0.04
S-S-S	4.0	24.9	9.6	.15	0.04
C-S-C	20.0	39.7	30.2	.20	0.04
S-C-S	20.0	35.7	33.6	.975	0.04
Other					
C-C-C	20.6	21.1	58.6	$ .75	$ 0.04
S-S-S	20.6	24.9	49.6	.20	0.04
C-S-C	40.0	39.7	60.5	.20	0.04
S-C-S	40.0	39.7	67.2	.75	0.04

C-C-C	trips within center
S-S-S	trips within suburb
C-S-C	round-trips from center to suburb
S-C-S	round-trips from suburb to center

TABLE F-8. BUS TRANSIT DATA, NEW YORK

(Boxes 1-5 of Figure F-1)

Trip Type	Round Trip Distance (miles)	Average Speed (mph)	Total In-Vehicle Time (minutes)	Round Trip Wait Time	Total Walk Time	Round Trip Fare
Work						
C-C-C	11.2	13	51.7	5.0	17.0	$ .70
S-S-S	11.2	15	44.8	6.0	16.0	.70
C-S-C	43.0	28	92.1	5.5	16.0	1.50
S-C-S	43.0	28	92.1	5.5	17.0	1.50
Shop						
C-C-C	2.0	14	8.5	12.0	17.0	$ .70
S-S-S	4.0	16	15.0	16.0	16.0	.70
C-S-C	20.0	30	40.0	14.0	16.0	1.00
S-C-S	20.0	30	40.0	14.0	17.0	1.00
Other						
C-C-C	20.6	14	88.2	12.0	17.0	$ .70
S-S-S	20.6	16	77.3	16.0	16.0	.70
C-S-C	40.0	30	80.0	14.0	16.0	1.70
S-C-S	40.0	30	80.0	14.0	17.0	1.70

C-C-C	trips within center	C-S-C	round-trips from center to suburb
S-S-S	trips within suburb	S-C-S	round-trips from suburb to center

TABLE F-9. RAIL TRANSIT DATA, NEW YORK

(Boxes 1-5 of Figure F-1)

Trip Type	Round Trip Distance (miles)	Average Speed (mph)	Total In-Vehicle Time (minutes)	Round Trip Wait Time	Total Walk Time	Round Trip Fare
Work						
C-C-C	11.2	25.0	26.9	4.0	17.0	$ .70
S-S-S	11.2	30.0	22.4	5.0	15.0	.70
C-S-C	43.0	40.0	64.5	4.5	16.0	1.70
S-C-S	43.0	40.0	64.5	4.5	16.0	1.70
Shop						
C-C-C	2.0	25.0	4.8	10.0	17.0	$ .70
S-S-S	4.0	30.0	8.0	12.0	15.0	.70
C-S-C	20.0	40.0	30.0	11.0	16.0	1.25
S-C-S	20.0	40.0	30.0	11.0	16.0	1.25
Other						
C-C-C	20.6	25.0	49.4	10.0	17.0	$ .70
S-S-S	20.6	30.0	41.2	12.0	15.0	.70
C-S-C	40.0	40.0	60.0	11.0	16.0	2.00
S-C-S	40.0	40.0	60.0	11.0	16.0	2.00

C-C-C trips within center
S-S-S trips within suburb
C-S-C round-trips from center to suburb
S-C-S round-trips from suburb to center

TABLE F-10. AUTO TRAVEL DATA, WASHINGTON, D. C.

(Boxes 1-5 of Figure F-1)

Trip Type	Round Trip Distance (miles)	Average Speed (mph)	Total In-Vehicle Time (minutes)	Fixed Cost Per Trip	Variable Cost Per Mile
Work					
C-C-C	12.2	20.0	36.6	$ 1.00	$ 0.04
S-S-S	12.2	23.2	31.6	0.20	0.04
C-S-C	28.4	33.8	50.9	0.20	0.04
S-C-S	28.4	29.0	58.7	1.00	0.04
Shop					
C-C-C	5.6	22.7	14.8	$ 0.20	$ 0.04
S-S-S	5.6	22.7	14.8	0.10	0.04
C-S-C	12.0	36.0	20.0	0.15	0.04
S-C-S	12.0	36.0	20.0	0.30	0.04
Other					
C-C-C	20.6	24.0	51.5	$ 0.10	$ 0.04
S-S-S	20.6	24.0	50.5	0.05	0.04
C-S-C	25.0	36.0	41.6	0.075	0.04
S-C-S	25.0	36.0	41.6	0.15	0.04

C-C-C	trips within center
S-S-S	trips within suburb
C-S-C	round-trips from center to suburb
S-C-S	round-trips from suburb to center

TABLE F-11. BUS TRANSIT DATA, WASHINGTON, D.C.

(Boxes 1-5 of Figure F-1)

Trip Type	Round Trip Distance (miles)	Average Speed (mph)	Total In-Vehicle Time (minutes)	Round Trip Wait Time	Total Walk Time	Round Trip Fare
Work						
C-C-C	12.2	11.6	63.0	6	17.0	$ .80
S-S-S	12.2	14.0	52.0	8	16.0	.80
C-S-C	28.4	28.0	60.8	7	16.5	1.80
S-C-S	28.4	25.0	68.2	7	16.5	1.80
Shop						
C-C-C	5.6	12.3	27.0	13	17.0	$ .80
S-S-S	5.6	15.6	21.0	18	16.0	.80
C-S-C	12.0	33.0	22.2	15	16.5	.90
S-C-S	12.0	33.0	22.2	15	16.5	.90
Other						
C-C-C	20.6	12.3	100.5	13	17.0	$ .80
S-S-S	20.6	15.6	79.2	18	16.0	.80
C-S-C	25.0	33.0	45.5	15	16.5	1.70
S-C-S	25.0	33.0	45.5	15	16.5	1.70

C-C-C trips within center
S-S-S trips within suburb
C-S-C round-trips from center to suburb
S-C-S round-trips from suburb to center

TABLE F-12. AUTO TRAVEL DATA, CHICAGO

(Boxes 1-5 of Figure F-1)

Trip Type	Round Trip Distance (miles)	Average Speed (mph)	Total In-Vehicle Time (minutes)	Fixed Cost Per Trip	Variable Cost Per Mile
Work					
C-C-C	13.8	18.6	44.5	$ 1.00	$ 0.04
S-S-S	13.8	20.6	40.2	.20	0.04
C-S-C	33.0	29.3	67.6	.20	0.04
S-C-S	33.0	27.0	73.3	1.00	0.04
Shop					
C-C-C	4.0	22.2	10.8	$ .15	$ 0.04
S-S-S	4.0	22.2	10.8	.10	0.04
C-S-C	15.0	33.0	27.3	.10	0.04
S-C-S	15.0	33.0	27.3	.20	0.04
Other					
C-C-C	20.6	22.2	56.2	$ .10	$ 0.04
S-S-S	20.6	22.2	56.2	.05	0.04
C-S-C	30.0	33.0	54.6	.05	0.04
S-C-S	30.0	33.0	54.6	.10	0.04

C-C-C	trips within center
S-S-S	trips within suburb
C-S-C	round-trips from center to suburb
S-C-S	round-trips from suburb to center

TABLE F-13. BUS TRANSIT DATA, CHICAGO

(Boxes 1-5 of Figure F-1)

Trip Type	Round Trip Distance (miles)	Average Speed (mph)	Total In-Vehicle Time (minutes)	Round Trip Wait Time	Total Walk Time	Round Trip Fare
Work						
C-C-C	13.8	10.7	77.4	6	17.0	$ .80
S-S-S	13.8	13.0	63.7	8	16.0	.80
C-S-C	33.0	24.0	76.0	7	16.5	1.10
S-C-S	33.0	22.0	82.5	7	16.5	1.10
Shop						
C-C-C	4.0	11.8	20.3	13	17.0	$ .80
S-S-S	4.0	15.7	15.3	18	16.0	.80
C-S-C	15.0	29.0	31.0	15	16.5	.80
S-C-S	15.0	29.0	31.0	15	16.5	.80
Other						
C-C-C	20.6	11.8	105.0	13	17.0	$ .80
S-S-S	20.6	15.7	78.7	18	16.0	.80
C-S-C	30.0	29.0	62.0	15	16.5	1.10
S-C-S	30.0	29.0	62.0	15	16.5	1.10

C-C-C	trips within center	C-S-C	round-trips from center to suburb
S-S-S	trips within suburb	S-C-S	round-trips from suburb to center

TABLE F-14. RAIL TRANSIT DATA, CHICAGO

(Boxes 1-5 of Figure F-1)

Trip Type	Round Trip Distance (miles)	Average Speed (mph)	Total In-Vehicle Time (minutes)	Round Trip Wait Time	Total Walk Time	Round Trip Fare
Work						
C-C-C	13.8	23.0	36.0	4.0	18	$ .90
S-S-S	13.8	34.4	24.0	5.0	16	.90
C-S-C	33.0	36.0	55.0	4.5	17	1.25
S-C-S	33.0	36.0	55.0	4.5	17	1.25
Shop						
C-C-C	4.0	22.8	17.9	10.0	18	$ .90
S-S-S	4.0	27.2	15.0	12.0	16	.70
C-S-C	15.0	38.0	23.7	11.0	17	.90
S-C-S	15.0	38.0	23.7	11.0	17	.90
Other						
C-C-C	20.6	22.8	54.2	10.0	18	$ .90
S-S-S	20.6	27.2	45.4	12.0	16	.90
C-S-C	30.0	38.0	47.4	11.0	17	1.25
S-C-S	30.0	38.0	47.4	11.0	17	1.25

C-C-C	trips within center	C-S-C	round-trips from center to suburb
S-S-S	trips within suburb	S-C-S	round-trips from suburb to center

Parameter Estimates for Mode Split and Trip Frequency Equations and the Value of Time (Boxes 6-8)

The mode split equations (Box 6 in Figure F-1) have the following form:

$$\log \frac{H}{1-H} = a_0 + a_1 \times TW + a_2 \times (AIV - TSS) + a_3 \times (AC - FARE)$$

where H = probability an individual will choose the auto mode rather than a transit mode

TW = transit walk time

AIV = automobile in-vehicle time

TSS = transit station-to-station time plus wait time

AC = automobile costs for parking, tolls

FARE = transit fare

The values used for the parameters (a_0, a_1, a_2, and a_3) are shown in Table F-15. The constant term (a_0) has been recalibrated for each study region.

We can now use the mode split equation parameters to calculate the value of time and the total cost of a transit trip. The total cost of a trip (Box 8 of Figure F-1) is calculated by adding three cost components: the cost of waiting time, the cost of in-vehicle time, and the out-of-pocket costs. Data on out-of-pocket costs were presented in the last section. We can derive an estimate for the value of waiting and in-vehicle time from the Domencich and McFadden mode-split coefficients.

The mode split equation for shopping trips has the following form:

$$\log \frac{H}{1-H} = -6.77 + .374TW - .0654 (AIV-TSS) - 4.11(AC-FARE)$$

where the variables are as defined above.

Let $y = \log \frac{H}{1-H}$. Then

$$\frac{\partial FARE}{\partial TW} = \frac{\partial y}{\partial TW} \bigg/ \frac{\partial y}{\partial FARE} = \frac{.374}{-4.11} = -.09 \ ,$$

This means that the transit fare would have to be decreased 9¢ to compensate for a one-minute increase in walk time. Therefore the value of transit walk time can be estimated at 9¢/minute. Analagously, the value of riding time can be estimated at

$$\frac{\partial FARE}{\partial TSS} = \frac{.0654}{-4.11} = -.02$$

or 2¢/minute.

TABLE F-15. MODE SPLIT PARAMETERS

(Box 6 in Figure F-1)

Mode Split Equation Recalibrated Constant Terms (a_0)--

	Los Angeles		New York		Washington, D. C.		Chicago	
	Work Trip	Shopping Trip	Work Trip	Shopping Trip	Work Trip	Shopping Trip	Work Trip	Shopping Trip
C-C-C	-.05	-3.98	- .36	-5.87	-1.45	-7.50	- .28	-5.18
S-S-S	.98	-3.37	1.38	-4.08	- .98	-5.25	- .65	-4.33
C-S-C	-.05	-3.98	-2.49	-5.77	- .45	-6.00	.32	-5.18
S-C-S	.98	-3.37	.73	-4.28	.43	-6.60	1.95	-4.33

Note: We used the same constant for "other" trips as for shopping trips. In their study of Pittsburgh, Domencich and McFadden estimated the constant term for Pittsburgh at -4.77 for work trips and -6.77 for shopping trips.

C-C-C	trips within center
S-S-S	trips within suburb
C-S-C	round-trips from center to suburb
S-C-S	round-trips from suburb to center

Mode Split Equation Parameters--

	a_1	a_2	a_3
Work trips	.114	-.0411	-2.24
Shopping trips	.374	-.0654	-4.11

Note: Estimated by Domencich and McFadden from a survey of trip behavior in Pittsburgh by the Southwestern Pennsylvania Regional Planning Commission. Their equations included an additional variable. We have used the same coefficients for "other" trips as for shopping trips.

Source: A Disaggregated Behavioral Model of Urban Travel Demand, Charles River Associates (1972).

The cost of a transit trip has the following three components:

$$(TW \times .09) + (TSS \times .02) + FARE$$

Turning now to the calculation of trip frequencies, the trip-frequency equation (Box 7 in Figure F-1) has the following form:

$$\log \frac{HF}{1-HF} = b_0 + b_1 P$$

where HF = probability an individual will take a trip

P = trip price

It is assumed that $HF = 1$ for work trips.

The values used for the parameters (b_0 and b_1) are shown in Table F-16.

Potential Trips (Boxes 9-11)

Three inputs are needed for the calculation of potential trips: city center and suburb population and growth factors (Boxes 9 and 10 of Figure F-1) and a matrix of potential trip factors (Box 11 of Figure F-1).

We have used the number of potential trip-takers as a proxy for the number of potential trips (round trips). For work trips we can safely assume that the number of trips equals the number of travelers: that is, that each worker makes an average of one work trip a day. The potential travelers for a work trip wholly within the central city would be, for example, that fraction of total central city population who work in the central city. The matrix below gives the distribution of work trips by origin and destination for New York in 1970:

TABLE F-16. TRIP FREQUENCY PARAMETERS

(Box 7 of Figure F-1)

Trip Frequency Equation Recalibrated Constant Terms (b_0)--

	Los Angeles		New York		Washington, D. C.		Chicago	
	Shopping Trips	Other Trips	Shopping Trips	Other Trips	Shopping Trips	Other Trips	Shopping Trips	Other Trips
Auto	2.8	4.1	3.7	4.7	3.8	6.4	2.9	5.1
Bus	6.7	9.8	0.0	0.0	5.2	7.4	6.0	7.00
Rail	--	--	3.1	4.6	--	--	5.6	7.4

Note: Domencich and McFadden estimated the constant for Pittsburgh shopping trips at 3.9.

Trip Frequency Equation Parameters--

	b_1
Shopping Trips	-1.72

Note: We have used the same price coefficient for "other" trips as for shopping trips.

Source: A Disaggregated Behavioral Model of Urban Travel Demand, Charles River Associates (1972).

WORK TRIPS - NEW YORK CITY

(1000's of Trips)

		Working In:			
		C	S	Total	Population
Living In	C	2549	99	2648	7346
	S	335	890	1225	3341
Total		2885	989	3874	10778

Source: Urban Transportation Factbook, American Institute of Planners and Motor Vehicle Manufacturers Association (1974).

Note: C - city center; S - suburb

Using the above data, we calculate the base year (1970) proportion of the population who are workers, for each origin-destination pair:

		Working in:	
		C	S
Living In	C	.347	.013
	S	.100	.266

The product of these ratios with current population is the number of total potential work trips (travelers) between a given origin and destination (O-D). For New York, for example, the work-trip matrix of potential trip factors and how it is used in the calculations of the transportation module are shown below:

Total Potential Work
Trips (Travelers) With
O-D Combination:

$$\underset{(4\times 1)}{\begin{bmatrix} \text{C-C-C} \\ \text{S-S-S} \\ \text{C-S-C} \\ \text{S-C-S} \end{bmatrix}} = \overset{\text{Work Trip Matrix}}{\underset{(4\times 2)}{\begin{bmatrix} .347 & 0.0 \\ 0.0 & .266 \\ .013 & 0.0 \\ 0.0 & .100 \end{bmatrix}}} \times \overset{\text{Population}}{\underset{(2\times 1)}{\begin{bmatrix} Pop_c \\ Pop_s \end{bmatrix}}}$$

where Pop_c and Pop_s refer to central city and suburb population, respectively, and the numbers in parentheses are the matrix dimensions.

It is more problematic to determine the number of "potential" trips for shopping and "other" purposes. Whereas a worker takes one daily work trip and a non-worker does not, no similar distinction can be made between potential shoppers and non-shoppers. We have assumed that the number of trips is proportional to the number of households. We have also assumed that in any given year the average daily number of shopping trips per household will not be greater than one, although the average number of trips taken by those households actually taking trips on a given day may be greater than one.

As in the case of work trips, potential trip factors are calculated for shopping and "other" trips. Here a base year ratio (also 1970) of households to total population in the origin is multiplied by current population. This yields current number of households in the origin, our proxy for (number of) potential trips.

The inputs used in the numerical calculations reported in this study are shown in Table F-17.

Vehicle Occupancy Rates (Box 12)

The final input needed by the Transportation Module, vehicle occupancy rates (Box 12 of Figure F-1), are used to translate passenger miles into vehicle miles. These data are shown in Table F-18.

Calibration Data

To calibrate the Transportation Module, data on actual vehicle miles traveled for a base year (1975) were obtained. These data are shown in Table F-19.

EMISSIONS MODULE INPUTS

The Emissions Module requires five kinds of input:

a) Automobile mileage
b) Emission factors
c) Deterioration factors
d) Automobile speeds
e) Control device efficiencies

Automobile Mileage

The distributions of annual automobile miles traveled by each age automobile are shown in Table F-20. These distributions and forecasted vehicle miles of travel (provided by the Transportation Module) are used to calculate the number of miles driven by each age of automobile.

TABLE F-17. POTENTIAL TRIP FACTORS, POPULATION, AND POPULATION GROWTH

(Boxes 9, 10, 11 of Figure F-1)

	Work Trip Matrix of Potential Trip Factors*	Shopping/Other Trip Matrix of Potential Trip Factors*
Los Angeles Center: Population 3.2 million Growth rate 0% Suburb: Population 6.4 million Growth rate 3%	$\begin{bmatrix} .267 & 0 \\ 0 & .237 \\ .094 & 0 \\ 0 & .109 \end{bmatrix}$	$\begin{bmatrix} .375 & 0 \\ 0 & .313 \\ .375 & 0 \\ 0 & .313 \end{bmatrix}$
New York Center: Population 7.9 million Growth rate 0% Suburb: Population 12.3 million Growth rate 1%	$\begin{bmatrix} .347 & 0 \\ 0 & .266 \\ .013 & 0 \\ 0 & .100 \end{bmatrix}$	$\begin{bmatrix} .3597 & 0 \\ 0 & .301 \\ .3597 & 0 \\ 0 & .301 \end{bmatrix}$
Washington, D. C. Center: Population .77 million Growth rate 0% Suburb: Population .99 million Growth rate 3%	$\begin{bmatrix} .285 & 0 \\ 0 & .260 \\ .069 & 0 \\ 0 & .130 \end{bmatrix}$	$\begin{bmatrix} .337 & 0 \\ 0 & .257 \\ .337 & 0 \\ 0 & .257 \end{bmatrix}$
Chicago Center: Population 3.3 million Growth rate 0% Suburb: Population 3.7 million Growth rate 3%	$\begin{bmatrix} .297 & 0 \\ 0 & .274 \\ .062 & 0 \\ 0 & .098 \end{bmatrix}$	$\begin{bmatrix} .300 & 0 \\ 0 & .336 \\ .300 & 0 \\ 0 & .336 \end{bmatrix}$

* The matrices contain the potential trip factors. Matrix rows represent origin-destination pairs in the following order:

C-C-C	trips within center
S-S-S	trips within suburb
C-S-C	round-trips from center to suburb
S-C-S	round-trips from suburb to center

Matrix columns represent the center and suburb, respectively. The way a matrix is used in calculations is illustrated in the text.

TABLE F-18. VEHICLE OCCUPANCY INPUT DATA
(Box 12 of Figure F-1)

	AUTO		BUS		RAIL	
	Work	Shop/ Other	Work	Shop/ Other	Work	Shop/ Other
New York	1.20	1.15	34	17	70	15
Chicago	1.23	1.18	40	18	44	20
Los Angeles	1.1	1.4	30	14	—	—
Washington, D.C.	1.3	1.2	42	21	—	—

Source: estimated.

TABLE F-19. DAILY VEHICLE MILE TRAVELED (VMT) FOR BASE YEAR CALIBRATION

Region	1970 VMT/Day+ (10^6)	Annual Growth Rate++ (%)	Geographical Factor+++	1975 VMT/Day (10^6)
New York (Tri-State Region)				
Auto				200
Bus				.6
Rail				1.2
Chicago Region				
Auto	84	1	1.3	113
Bus	.269	1	1.3	.365
Rail	.14*			.6**
Washington, D. C. Region				
Auto	33.1	2		36.5
Bus	.0897	2		.099
Los Angeles Region				
Auto	144.0	2		159.0
Bus	.217	2		.24

* Rapid transit only

** Estimated

Sources: + Urban Transportation Factbook, American Institute of Planners and Motor Vehicle Manufacturers Association, (1974), Tables I22, I43.

++ Based on 1960-1970 population growth as reported in Factbook p. I-9. Assumed growth rates are approximately two-thirds those for 1960-1970.

+++ Where 1970 figures are for the city alone, the geographical factor is the ratio of the metropolitan area population to city population. (Factbook, p. II-21 for Chicago.) Resulting 1975 figures are estimates for the region.

New York (Tri-State Region) bus and rail figures are projected to 1975 from Table II and Chart II of the Status of Regional Public Transportation Service and Use - 1972 (May 1974). The automobile figure is projected from Vehicle Miles of Travel on Major Roadways, 1970 (November 1973). Both documents are published by the Tri-State Regional Planning Commission. [New York rail VMT assumes ten cars to a train.]

TABLE F-20. DISTRIBUTION OF TOTAL ANNUAL MILES BY AGE OF AUTOMOBILE

Age of Automobile (in years)	Percent of Total Miles Traveled by Automobile of Given Age		
	Series A	Series B	Series C
1	9.75	8.67	12.42
2	8.86	7.88	10.88
3	7.69	7.23	10.28
4	6.80	6.31	8.23
5	6.24	6.17	7.20
6	5.74	5.71	6.00
7	5.41	5.65	4.54
8	4.91	5.32	4.28
9	4.63	4.79	3.77
10	4.35	4.60	3.60
11	4.13	4.37	3.42
12	3.92	4.15	3.25
13	3.73	3.94	3.09
14	3.54	3.74	2.93
15	3.36	3.56	2.78
16	3.20	3.38	2.64
17	3.04	3.21	2.51
18	2.88	3.05	2.39
19	2.74	2.90	2.27
20	2.60	2.75	2.15
21	2.47	2.61	2.05
Total*	100.00	100.00	100.00

Source: Series A was obtained from a study of air quality programs in the Chicago metropolitan area conducted by G. S. Tolley of the University of Chicago.

Series B is the national average reported in T. A. Bostich and H. J. Greenbalgh, "Relationship of Passenger Car Age and Other Factors to Mileage Driven," U. S. Department of Commerce, Bureau of Public Roads. Washington, D. C., 1967.

Series C is a Los Angeles basin-specific distribution from "The Economics of Air Pollution Control for Used Cars," by Lytton Stoddard and Paul Downing, University of California, Riverside, Working Paper No. 15.

We used Series A for Chicago and New York, Series B for Washington, D. C., and Series C for Los Angeles.

* Totals may not equal exactly 100% due to rounding. It is assumed that vehicles older than 21 years are driven a negligible amount of miles annually.

Emission Factors

Emissions data for automobiles, for other mobile sources, and for stationary sources are shown in Tables F-21 through F-29. Table F-21 shows EPA estimates of new automobile emissions of carbon monoxide, exhaust hydrocarbons, and nitrogen oxides in grams per mile for cars made before 1975 in compliance with EPA standards.[*] A high emission-rate scenario was developed for new cars in Los Angeles based on measurements from a more recent EPA study. These estimates are presented in Table F-22 and are used to test the sensitivity of MATHAIR to automobile emission assumptions. Table F-23 shows other automobile emissions (non-exhaust hydrocarbons and sulfur oxides). Table F-24 describes the scenario for the lead content of automobile fuel used in our simulations. Bus emission factors are shown in Table F-25. The other categories of emissions are calculated on a tons per day basis. Tables F-26 to F-29 show these emissions data.

Deterioration Factors

The emission performance of automobiles deteriorates with age. Deterioration factors are shown in Tables F-30 and F-31.

Automobile Speeds

The emission characteristics discussed above are for automobiles driven at 20 miles per hour. Assumed average automobile speeds for the four study regions are shown in Table F-32 and speed correction curves are shown in Figure F-2.

Control Devices

The final type of input required is the efficiency of control devices in reducing emissions. These data are presented along with the device costs in the final section of this appendix entitled "Cost Module Inputs."

AIR QUALITY MODULE INPUTS

The Air Quality Module requires user-specified rollback parameters. These are shown in Table F-33. The data used to calculate these parameters are shown in Table F-34.

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[*] California emissions are shown separately because emission control standards were implemented there on a different schedule from the Federal emission standards.

TABLE F-21. NEW CAR EXHAUST EMISSIONS

(grams/mile)

Year	California			Non-California		
	Carbon Monoxide (CO)	Hydrocarbon (HC)	Nitrogen Oxides (NO_x)	Carbon Monoxide (CO)	Hydrocarbon (HC)	Nitrogen Oxides (NO_x)
Pre 1966	87	8.8	3.6	87	8.8	3.6
1966	51	6.0	3.4	87	8.8	3.6
1967	50	4.6	3.4	87	8.8	3.6
1968	46	4.5	4.3	46	4.5	4.3
1969	33	4.4	5.5	39	4.4	5.5
1970	36	3.6	5.1	36	3.6	5.1
1971	34	2.9	3.5	34	2.9	4.8
1972	19	2.7	3.5	19	2.7	4.8
1973	19	2.7	2.3	19	2.7	2.3
1974	19	2.7	2.3	19	2.7	2.3
1975	2.8	.33	1.1	12.5	1.3	2.2

Source: Compilation of Air Pollutant Emission Factors, AP-42, EPA, (April 1973) and Supplement No. 2, (September 1973).

TABLE F-22. CALIFORNIA NEW CAR EXHAUST EMISSIONS: HIGH ESTIMATES

(grams/mile)

Year	CO	HC	NO_x
Pre 1966	87	8.8	3.6
1966	70	7.9	3.6
1967	65	7.1	3.6
1968	61	6.2	4.3
1969	56	5.3	5.5
1970	52	4.5	5.1
1971	47	3.6	3.8
1972	42	3.2	3.8
1973	37	3.2	3.1
1974	37	3.2	3.1
1975	5.4	.6	2.0

Source: These figures are based on those reported in Preliminary Edition of Supplement 5 to Compilation of Air Pollutant Emission Factors, AP-42, EPA (April 1975). We have rendered the CO and HC figures monotonic since the non-monotonicity of the corresponding measurements in Supplement 5 have yet to be verified.

TABLE F-23. OTHER AUTOMOBILE EMISSIONS

a. Non-Exhaust Hydrocarbon Emissions

	Pre 1971	1972 and later
Diurnal loss (grams per vehicle per day)	23.6	16.3
Running and Hot Soak Loss (grams per mile)	2.1	1.45

b. Sulfur Oxide Emissions

.13 grams per mile

Source:

a. Calspan Corporation, "Automotive Exhaust Emissions Surveillance, A Summary," EPA Report APTD 1544 (May, 1973). Data is derived from a test of 31 vehicles in Los Angeles.

b. Compilation of Air Pollutant Emission Factors, AP-42, EPA, April 1973 and Supplement No. 2, September 1973.

TABLE F-24. SCENARIO FOR LEAD CONTENT OF AUTOMOBILE FUEL

a. Demand for Lead-free Gasoline by Percent of Automobiles of each Model Year[a]

	(percent)
1971	15
1972	25
1973	35
1974	60
1975	85
1976	100

b. Lead Content of (Leaded) Gasoline

	(grams per gallon)
1975	1.70
1976	1.50
1977	1.25

Source:

a. John B. Moran, Lead in Gasoline: Impact of Removal on Current and Future Automotive Emissions, for Air Pollution Control Association, Denver, Colorado, June 9-13, 1974, Table 12, Scenario II or III (estimates by Bonner and Moore Associates).

b. Federal Register, vol. 7, No. 36, February 23, 1972, "Proposed Rule-Making: Regulation of Fuels and Fuel Additives."

TABLE F-25. BUS EMISSION FACTORS

(grams per mile)

Carbon Monoxide	20.4
Hydrocarbons	3.4
Nitrogen Oxides	24.0
Sulfur Oxides	2.4

Source: Compilation of Air Pollutant Emission Factors, AP-47, EPA, April 1973 and Supplement No. 2, September 1973.

TABLE F-26. HEAVY DUTY VEHICLE EMISSIONS

(tons/day)

	HEAVY DUTY GASOLINE			HEAVY DUTY DIESEL		
	CO	HC	NO_x	CO	HC	NO_x
Los Angeles	711.2	863.0	47.7	33.1	5.5	55.0
New York	2467.0	297.0	166.0	38.0	5.0	64.0
Washington, D.C.	183.0	21.5	12.0	2.9	0.5	5.0
Chicago	946.9	115.0	63.6	15.3	2.6	25.5

Sources: Los Angeles: data on total Los Angeles basin gas truck registrations in Appendix N of the Environmental Protection Agency's report APTD-1372 was multiplied by the average daily mileage (31) reported in MVMA's 1973 Motor Truck Facts to estimate VMT. VMT estimates were then used with emissions factors to arrive at total basin emissions. It was assumed (following data reported by an R. L. Polk Co. survey for New York City) that gas heavy duty vehicles are 90 percent of total truck population, giving an estimate of regional heavy duty diesel trucks. This estimate was then applied as above to get heavy duty diesel emissions. New York: an estimate of 3,757,000 daily VMT in the five counties area reported in Heavy Duty Vehicle Driving Pattern and Use Survey--New York City, (prepared for the Environmental Protection Agency by Wilbur Smith and Associates, May, 1973 - APTD-1523) was used (with 90-10 gas/diesel split) with emissions factors to estimate center city heavy duty emissions. Suburb emissions were estimated by multiplying center emissions by the ratio of suburb/center total vehicle VMT reported in the Environmental Protection Agency report APTD-1371. Chicago: total truck registrations for Chicago reported in MVMA's 1972 Auto Facts and Figures were used in a similar manner as discussed above for Los Angeles. Registrations were multiplied by average daily miles to get VMT which were in turn multiplied by emissions factors to get total emissions. Washington, D. C. data was not available for truck registrations or VMT. Judgmental estimates were made based on Chicago emissions data.

TABLE F-27. MOTORCYCLE EMISSIONS
(tons/day)

	CENTRAL CITY			SUBURB		
	CO	HC	NO_x	CO	HC	NO_x
Los Angeles	34.6	9.6	0.3	70.4	19.4	0.6
Other Cities		NOT ESTIMATED				

Source: Basin-wide population (107,500 2-stroke, 175,000 4-stroke) was multiplied by average miles driven per day (11) to get motorcycle vehicle miles traveled (VMT). Total VMT then was used to estimate total area emissions using Environmental Protection Agency report AP-42 emissions factors. A city-suburb split of 33/67 (based on population) was used to separate total basin emissions regionally.

TABLE F-28. STATIONARY SOURCE EMISSIONS

(tons/day)

	CO	HC	NO_x	SO_x
Los Angeles	175	444	245	228
New York	369	1,041	1,557	1,035
Washington, D. C.	33	24	81	142
Chicago	657	837	374	725

Source: Estimated from 1975 County Emission Summary Reports provided by the Data Processing Section, NEDS, EPA. Los Angeles region emissions assumed to be 43 percent (by population) of Los Angeles County emissions. New York data are estimated from 1974 Emissions Inventory Summary of New York City Department of Air Resources. New York region emissions assumed to be 300 percent of New York City emissions.

TABLE F-29. SPECIFIC STATIONARY SOURCE EMISSIONS

(Tons/day)

	Los Angeles			New York			Washington, D.C.			Chicago		
	CO	HC	NO_x	CO	HC	NO_x	CO	HC	NO_x	CO	HC	NO_x
Electricity Generation			158			870			39			170
Petroleum Industry		16	16		117						4	4
Industrial Evaporation		250			801			5			417	
Gasoline Handling		47						7			53	
Aircraft	45	20		111	66	42	7	2		37	17	12
Other Stationary Sources	130	111	71	258	57	645	26	10	42	620	346	188
Total	175	444	245	369	1041	1557	33	24	81	657	837	374

Source: Estimated from 1975 County Emissions Summary Reports provided by Data Processing Section, NEDS, EPA. New York data estimated from 1974 Emissions Inventory Summary of New York City Department of Air Resources. Washington, D.C. aircraft data estimated from Aircraft Emissions: Impact on Air Quality and Feasibility of Control, EPA (assumed 1972).

Notes: Los Angeles region emissions assumed 43 percent of Los Angeles County emissions; New York region emissions assumed 300 percent of New York City emissions. Fifty percent of "Miscellaneous Solvent Evaporation" assumed to be non-dry-cleaning industrial evaporation.

TABLE F-30. DETERIORATION FACTORS FOR LIGHT-DUTY, GASOLINE-POWERED VEHICLES IN ALL AREAS EXCEPT CALIFORNIA

Pollutant and Model Year	Vehicle Age, years									
	0	1	2	3	4	5	6	7	8	≥9
Carbon monoxide										
Pre 1968	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1968	1.00	1.24	1.35	1.41	1.47	1.53	1.58	1.63	1.67	1.72
1969	1.00	1.42	1.53	1.59	1.63	1.68	1.71	1.75	1.79	1.82
1970 through 1974	1.00	1.18	1.32	1.38	1.40	1.44	1.47	1.50	1.51	1.56
1975	1.00	1.04	1.30	1.36	1.43	1.44	1.49	1.56	1.63	1.69
Exhaust hydrocarbons										
Pre 1968	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1968	1.00	1.12	1.18	1.21	1.23	1.26	1.28	1.30	1.32	1.35
1969	1.00	1.10	1.16	1.18	1.21	1.23	1.25	1.28	1.29	1.31
1970 through 1974	1.00	1.05	1.10	1.13	1.15	1.17	1.20	1.22	1.24	1.26
1975	1.00	1.00	1.13	1.22	1.29	1.37	1.43	1.50	1.56	1.63
Nitrogen oxides										
Pre 1973	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1973 through 1974	1.00	1.11	1.18	1.20	1.21	1.22	1.23	1.24	1.25	1.26
1975	1.00	1.00	1.18	1.23	1.41	1.45	1.45	1.45	1.45	1.45

Source: Supplement No. 2 for Compilation of Air Pollutant Emission Factors, United States Environmental Protection Agency, (September 1973).

TABLE F-31. DETERIORATION FACTORS FOR LIGHT-DUTY, GASOLINE-POWERED VEHICLES IN CALIFORNIA

Pollutant and model year	Vehicle age, years									
	0	1	2	3	4	5	6	7	8	≥9
Carbon Monoxide										
Pre 1966	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1966	1.00	1.13	1.21	1.24	1.25	1.28	1.29	1.31	1.32	1.34
1967	1.00	1.11	1.18	1.23	1.29	1.35	1.40	1.46	1.50	1.56
1968	1.00	1.24	1.35	1.41	1.47	1.53	1.58	1.63	1.67	1.72
1969	1.00	1.42	1.53	1.59	1.63	1.68	1.71	1.75	1.79	1.82
1970 through 1974	1.00	1.18	1.32	1.38	1.40	1.44	1.47	1.50	1.51	1.56
Post-1974	1.00	1.16	1.34	1.50	1.62	1.75	1.88	2.00	2.10	2.22
Hydrocarbon										
Pre 1966	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1966	1.00	1.14	1.22	1.25	1.27	1.29	1.30	1.32	1.35	1.35
1967	1.00	1.07	1.10	1.12	1.14	1.15	1.17	1.18	1.20	1.21
1968	1.00	1.12	1.18	1.21	1.23	1.26	1.28	1.30	1.32	1.35
1969	1.00	1.10	1.16	1.18	1.21	1.23	1.25	1.28	1.29	1.31
1970 through 1974	1.00	1.05	1.10	1.13	1.15	1.17	1.20	1.22	1.24	1.26
Post 1974										
Nitrogen Oxides										
Pre 1970	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1971 through 1974	1.00	1.11	1.18	1.20	1.21	1.22	1.23	1.24	1.25	1.26
1975	1.00	1.03	1.07	1.10	1.13	1.17	1.19	1.21	1.24	1.26

Source: Supplement No. 2 for Compilation of Air Pollutant Emission Factors, United States Environmental Protection Agency, (September 1973).

TABLE F-32. ASSUMED AVERAGE AUTO SPEEDS

Region	Average Auto Speed (miles per hour)
Los Angeles	22
New York	20
Washington, D. C.	22
Chicago	20

Source: Based on _A Survey of Average Driving Patterns in Six Urban Areas in the United States_, Systems Development Corporation (1973).

TABLE F-33. ROLL-BACK PARAMETERS FOR AIR QUALITY MODULE

	Los Angeles	New York	Washington, D. C.	Chicago
CO	.00139	.00275	.01226	.00363
OX	.0000603	.000095	.000622	.000194
NO_x	.0000306	.000099	.000345	.0000634
SO_x	.00001026	.0000293	.000105	.0000627
Pb	.576	1.49	10.60	3.66

Source: Calculated from data in Table F-34.

TABLE F-34. DATA FOR CALCULATING ROLLBACK PARAMETERS

Area	Carbon Monoxide (CO)		Nitrogen Oxides (NO_x)		Oxidants (OX)		Sulfur Oxides (SO_x)		Particulates	
	Daily Emissions (Tons)	Maximum Concentration (ppm) (8 hr.)+	Daily Emissions (Tons)	Maximum Concentration (ppm) (annual arith. mean)+	Daily HC Emissions (Tons)	Maximum Concentration (ppm) (1 hr.)+	Daily Emissions (Tons)	Maximum Concentration (ppm) (annual arith. mean)+	Daily Emissions (Tons)	Max. Concentration (mg/m^3) (24 hr.)+
Los Angeles[c, e]	11,300	41	1,570	.094	3,200	.62	350	.020	170	604
New York[a, e]	14,330	20*	2,614	.08	2,985	.18	1,755	.018	486	280
Washington, D.C.[d, e]	2,349	29	203	.07	418	.26	148	.015	39	389
Chicago[b, e]	10,630	29	810	.08	1,895	.18	751	.022	603	897

a. Prediction of the Effects of Transportation Controls on Air Quality in Major Metropolitan Areas, APTD-1363, pp. 3-24.

b. Prediction of the Effects of Transportation Controls on Air Quality in Major Metropolitan Areas, APTD-1363, Tables Chl. 2, Chl. 1.

c. Transportation Control Strategy Development for the Metropolitan Los Angeles Region, APTD-1372, Table A-3 and Technical Support Document for the Metropolitan Los Angeles Intrastate Air Quality Control Region Transportation Control Plan Final Promulgation, United States Environmental Protection Agency Region IX, October 30, 1973, p. 2.

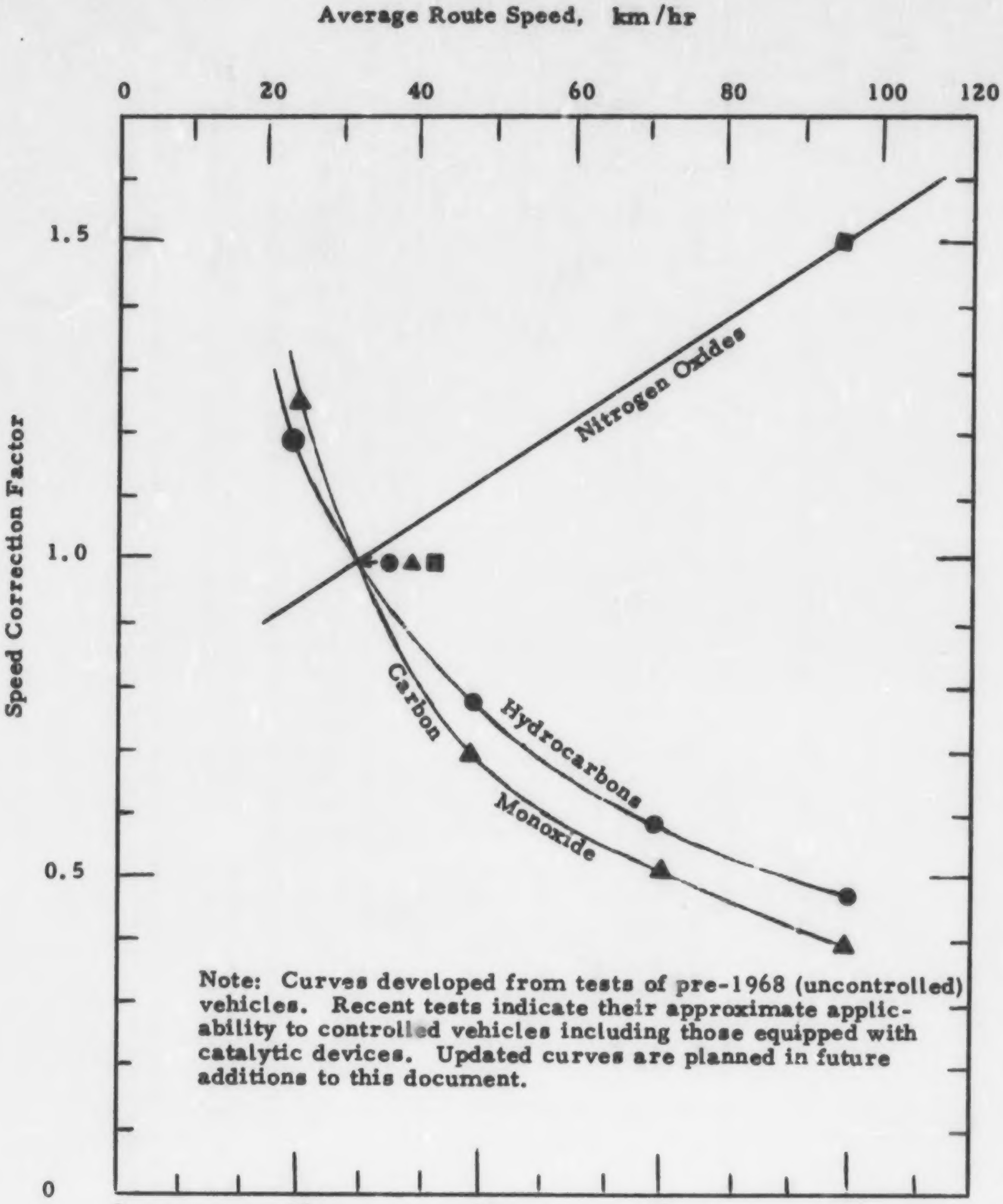
d. Estimated from Prediction of the Effects of Transportation Controls on Air Quality in Major Metropolitan Areas, APTD-1363, Table D.C.2, Table D.C.1.

e. All data on SO_x and particulate emissions (for 1971-1972) were obtained by telephone communication with the respective regional EPA offices. SO_x and particulate concentration data are from Air Quality Data, 1972 Annual Statistics, EPA, March 1974.

+ Averaging time

* This figure is the second largest concentration measured (maximum is 47 ppm). Since the maximum represents one measure at the most heavily polluted section of Manhattan, we decided to use the second largest

FIGURE F-2. AVERAGE SPEED CORRECTION FACTORS FOR ALL MODEL YEARS



Note: Curves developed from tests of pre-1968 (uncontrolled) vehicles. Recent tests indicate their approximate applicability to controlled vehicles including those equipped with catalytic devices. Updated curves are planned in future additions to this document.

Source: Compilation of Air Pollutant Emission Factors, United States Environmental Protection Agency, AP42, Supplement No. 2 (September, 1973).

BENEFITS MODULE INPUTS

The Benefits Module requires base year damages and air quality inputs. We have taken 1968 as the base year. Damage estimates are shown in Tables F-35 and F-36. Corresponding base year emissions are presented in Table F-37.*

COST MODULE INPUTS

In this section we present the control device costs for automobiles (Tables F-38 through F-41) and stationary sources (Tables F-42 through F-55) that are used in our simulations. All costs are presented in 1973 dollars.

The tables also indicate the efficiency of the devices.** We found it convenient to report device costs and efficiencies in one table, even though the costs are input to the Cost Module and the device efficiencies are input to the Emissions Module.

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* Air quality is calculated by applying the rollback coefficients to emissions. We realized after the study was completed that, in the standard case strategy simulations, 1970 emissions were used with 1968 damage estimates. The 1970 emissions are about 5-10% lower than 1968 emissions (due to intervening controls) and therefore produce an error of a 5-10% overestimate of damages per unit of pollutant (and of benefits per unit reduced by air pollution controls).

** Only costs are reported (in Tables F-38 and F-39) for bringing automobiles up to 1975 standards. Accompanying pollution reduction efficiency is reflected in emission estimates.

TABLE F-35. BASE YEAR DAMAGE ESTIMATES BY POLLUTANT AND DAMAGE CATEGORY
(millions of 1973 dollars, inflated from 1968 dollars using Wholesale Price Index)

	Carbon Monoxide (CO)	Oxidants (OX)	Nitrogen Oxides (NO_x)	Sulfur Oxides (SO_x)	Lead* (PB)
Los Angeles					
Health	8.95	85.36	53.66	--	1.17
Materials	23.11	267.41	73.05	--	2.22
Vegetation	--	20.34	13.90	--	.31
New York					
Health	1.38	14.39	17.03	278.21	.24
Materials	48.25	377.71	390.47	3189.60	5.68
Vegetation	--	.52	1.22	44.74	.01
Washington, D.C.					
Health	.30	1.08	.36	--	.01
Materials	13.43	55.63	7.75	--	.44
Vegetation	--	.64	.23	--	.01
Chicago					
Health	.89	10.22	39.12	139.81	.16
Materials	17.58	266.27	439.59	1010.78	2.27
Vegetation	--	2.11	8.72	83.88	.04

Source: Computed from air quality exceedance factors, exposure factors, and severity factors and total U.S. damages from Barrett and Waddell (1971) extended by Babcock and Nagda (1973). all reported in Justus *et al.*, *Economic Costs of Air Pollution Damage*, STAR, Inc., (May 1973).

*Pb estimated as 1.4 percent of particulates (33 percent of transportation sources and 1 percent of industrial process losses), based on Table 20 of Waddell, *Economic Damages of Air Pollution*, EPA (1974) and Ter Haar *et al.*, "Composition, Size and Control of Automotive Exhaust Particulates," *APCA* Journal, Vol. 22, No. 1, p. 43, (January 1972).

TABLE F-36. BASE YEAR LOW DAMAGE ESTIMATES BY POLLUTANT AND DAMAGE CATEGORY

(millions of 1973 dollars, inflated from 1970 dollars Using Wholesale Price Index)

	Carbon Monoxide (CO)	Oxidants (OX)	Nitrogen Oxides (NO_x)	Sulfur Oxides (SO)	Lead (Pb) *
Los Angeles					
Health	1.02	12.02	4.48	--	.17
Materials	2.63	37.64	6.10	--	.33
Vegetation	--	2.86	1.16	--	.05
New York					
Health	.16	2.03	1.42	10.75	.03
Materials	5.50	53.16	32.62	123.20	.84
Vegetation	--	.07	.10	1.73	--
Washington, D.C.					
Health	.04	.15	.03	--	--
Materials	1.53	7.83	.65	--	.07
Vegetation	--	.09	.02	--	--
Chicago					
Health	.10	1.44	3.27	5.40	.02
Materials	2.00	37.48	36.72	39.04	.34
Vegetation	--	.30	.73	3.24	.01

Source: Computed from air quality exceedance factors, exposure factors, severity factors, and lower bound of total U.S. damages reported in Justus et al, Economic Costs of Air Pollution Damage, STAR, Inc. (May 1973).

*Pb estimated as 1.4 percent of particulates (33 percent of transportation sources and 1 percent of industrial process losses), based on Table 20 of Waddell, Economic Damages of Air Pollution, EPA (1974) and Ter Haar, et al., "Composition, Size and Control of Automotive Exhaust Particulates, APCA Journal, Vol. 22, No. 1, p. 43, (January 1972).

TABLE F-37. BASE YEAR 1970 MOBILE AND STATIONARY SOURCE EMISSIONS

(tons per day)

	Mobile	Stationary
Los Angeles		
CO	5709	148
HC	922	578
NO_x	470	214
SO_x	28	300
Pb	57	———
New York		
CO	11778	782
HC	2106	794
NO_x	952	1928
SO_x	37	1432
Pb	12	———
Washington, D.C.		
CO	2014	19
HC	323	36
NO_x	146	49
SO_x	1.4	142
Pb	2.4	———
Chicago		
CO	8633	683
HC	1301	317
NO_x	483	311
SO_x	27	725
Pb	47	———

Source: Estimated from pages 3 - 10, 4 - 10, 3 - 28, 3 - 66 of Prediction of the Effects of Transportation Controls on Air Quality in Major Metropolitan Areas, APTD-1363 (November 1972).

SO_x estimates from 1975 County Emission Summary Reports Provided by the Data Processing Section, NADB, EPA.

Pb estimated from 1975 MATHAIR predictions adjusted to 1970 in proportion to average change in other mobile source pollutants.

TABLE F-38. PER VEHICLE ESTIMATES FOR POST-1967 CONTROL POLICIES EXCLUDING CALIFORNIA (1973 dollars)

Automobile Vintage	Equipment Cost	Annual Fuel Cost[a]	Annual Maintenance Cost
1968	$ 5.40	$15	$16.00
1969	5.40	18	16.00
1970	34.50	16	16.00
1971	34.50	26	16.00
1972	34.50	25	16.00
1973	82.50	34	16.00
1974	82.50	31	16.00
1975[b]	177.50 267.50	10 20[c]	13.00 20.00

a. Percentage loss converted to dollars assuming 10,000 miles/year, 13.1 miles/gallon, $.52/gallon.

b. The first figure is without catalytic convertor; the second includes its cost.

c. Assumed.

Source: The Cost of Clean Air Annual Report of the Administrator Environmental Protection Agency to the Congress of the United States (April 1974), Tables III-4, III-6, III-7. All costs are EPA estimates either stated or assumed to be 1973 dollars. For example, dollar figures cited in the Report from a 1972 EPA publication but not revised by EPA are assumed to be 1973 estimates.

TABLE F-39. PER VEHICLE ESTIMATES FOR POST-1965 CONTROL IN CALIFORNIA (1973 dollars)

Automobile Vintage	Equipment Cost	Annual Fuel Cost[a]	Annual Maintenance Cost
1966*	$ 4.00	$11.25	$12.00
1967*	1.10	3.00	3.20
1968*	.30	.75	.80
1969	5.40	18.00	16.00
1970	34.50	16.00	16.00
1971	34.50	26.00	16.00
1972	34.50	25.00	16.00
1973	82.50	34.00	16.00
1974	82.50	31.00	16.00
1975[b]	177.50 267.50	10.00[c] 20.00[c]	13.00 20.00

a. Percentage loss converted to dollars assuming 10,000 miles/year, 13.1 miles/gallon, $.52/gallon.

b. The first figure is without catalytic convertor; the second includes its cost.

c. Assumed

* Estimated

Source: The Cost of Clean Air Annual Report of the Administrator Environmental Protection Agency to the Congress of the United States (April 1974), Tables III-4, III-6, III-7. All costs are EPA estimates either stated or assumed to be 1973 dollars. For example, dollar figures cited in the document from a 1972 EPA publication but not revised by EPA in 1973 are assumed to be 1973 estimates.

TABLE F-40. EFFECTIVENESS, COST, AND FUEL CONSUMPTION BENEFIT OR PENALTY OF INSPECTION AND MAINTENANCE AND OF RETROFITS (1973 dollars+)

	VSAD	Air Bleed	Catalyst	Inspection and Maintenance *
Applicability	Pre-1968 Pre-1966 in Calif.	Pre-1972	20% of 1968-70 cars 75% of 1971-74 cars	All Cars
CO Reduction	9%	58% (pre-1968 cars) 40% (1968-71 cars)	50%	10%
HC Reduction	25%	21% (pre-1968 cars) 25% (1968-71 cars)	50%	10%
NO_x Reduction	23%	0	0	0
Installed Cost	$20	$20-$60	$125-$200	0
Annual Maintenance Cost	$ 5	$ 7	$ 25 biennially	$4
Fuel Benefit (+) or	-2% ($-10)	+0-4% (+$0-20)	Negligible	+2% (+$10)

+ 1973 dollars assumed; not indicated on tables.

* Inspection and maintenance cost figures are estimated from Horowitz, J. and S. Kuhrtz, Transportation Controls to Reduce Automobile Use and Improve Air Quality in Cities, EPA-400/11-74-002 (November 1974).

Source: Horowitz, J., Transportation Controls, Table II. Document undated, early 1974 assumed.

TABLE F-41. DESCRIPTION OF THREE-WAY CATALYTIC CONVERTOR

Proportion Emission Reduction (over 1975)		
CO	HC	NO_x
.73	.69	.82

Device Cost Components:

Installed Cost: $370
Annual Additional Fuel Cost: $40
Annual Additional Maintenance: $23

Source: Estimated from Report by the Committee on Motor Vehicle Emissions, National Academy of Science (November 1974), Table V-4, p. 89. Proportion emission reduction is that between 1975 and 1978 emissions assumed in the document.

TABLE F-42. UNIT COST AND EFFECTIVENESS OF CONTROLS APPLIED TO HYDROCARBON (HC) EMISSIONS FROM PRINTING[a] (1973 dollars)

Emissions Control	HC Emissions Tons/Year	Percent Reduction	Change in Emissions Tons/Year	Annual Cost	Capital Cost
None	4.72				
Thermal Incinerator[b]	1.77	63	2.95	$13,500	$31,000
Catalytic Incinerator[b]	.59	88	4.13	12,900	50,000

[a] Assumes as a "standard" a web ffset litho/letter press, 5000 scfm, emitting 5lbs/hr, 8 hrs/day, 260 days/yr.

[b] These control alternatives are mutually exclusive.

Source: Computations based on data in Systems and Costs to Control Hydrocarbon Emissions from Stationary Sources, U.S. EPA Emission Standards and Engineering Division (August 1973), p. 16.

TABLE F-43. UNIT COST AND EFFECTIVENESS OF CONTROLS APPLIED TO HYDROCARBON (HC) EMISSIONS FROM DEGREASING[a]

(1973 dollars)

Emissions Control	HC Emissions Thousand-Tons/Year	Percent Reduction	Change in Emission Thousand-Tons/Year	Annual Cost	Capital Cost
None	31.14				
Temperature controls plus careful operation	18.87	39	12.27	($1,428)	$ 300
Temperature controls plus refrigerating cooling coils[b]	15.48	18	3.39	(1,070)	3,000
Carbon absorption[b]	3.02	90	28.12	(620)	19,500

[a] Assumes as a standard open tank vapor decreases operating 40 hours/week, 29 ft^2 tank, uncontrolled emission rate = .825 $lbs/hr\text{-}ft^2$.

[b] These control alternatives are mutually exclusive.

Note: Numbers in parentheses indicate cost savings due to recovery of solvents.

Source: Computations based on data in Systems and Costs to Control Hydrocarbon Emissions from Stationary Sources, U.S. Environmental Protection Agency, Emission Standards and Engineering Division (August 1973), pp. 5 - 8.

TABLE F-44. UNIT COST AND EFFECTIVENESS OF CONTROLS APPLIED TO HYDROCARBON (HC) EMISSIONS FROM PETROLEUM STORAGE[a] (1973 dollars)

Emissions Control	HC Emissions Tons/Year	Percent Reduction	Change in Emissions Tons/Year	Annual Cost	Capital Cost
None	176.8				
Pontoon floating roof	12.7	93	164.1	$ 0	$25,000

[a] Assumes a standard storage tank at 90' diameter with a 50,000 BBL capacity.

Source: Computations based on data in Systems and Costs to Control Hydrocarbon Emissions from Stationary Sources, op. cit, p. 24 and Hydrocarbon Pollutant Systems Study, EPA contract No. 71-12, MSA Research Corporation, vol. 1 (1972).

TABLE F-45. UNIT COST AND EFFECTIVENESS OF CONTROLS APPLIED TO HYDROCARBON (HC) EMISSIONS FROM GASOLINE MARKETING[a] (1973 dollars)

Emissions Control	HC Emissions Tons/Year	Percent Reduction	Change in Emissions Tons/Year	Annual Cost	Capital Cost
None	881.3				
Vapor recovery at terminal	645.6 645.6	27	235.8	$21,000	$235,000
Vapor recovery at terminal plus recycle vapor to truck	382.4	41	263.1	29,000	322,000
Plus carbon cannister[b]	69.4	82	313.0	390,000	1,827,000
Plus refrig. condensation[b]	69.4	82	313.0	808,000	3,800,000

[a] Assumes standard hypothetical gasoline distribution system with the following parameters: Terminal flow = 250 x 10^3 gal/day; Number of stations = 300; Number of tank trucks = 15 Top Loading; Normal summer operating conditions.

[b] These control alternatives are mutually exclusive.

Source: Computations based on data in Systems and Costs to Control Hydrocarbon Emissions from Stationary Sources, U.S. Environmental Protection Agency, Emission Standards and Engineering Division, August 1973, pp. 27-29.

TABLE F-46. UNIT COST AND EFFECTIVENESS OF CONTROLS APPLIED TO THE EMISSIONS FROM AIRCRAFT TURBINE ENGINES[a] (1973 dollars)

Emissions Control	THC Emissions Thousand Tons/Year	Percent Reduction	Change in Emission Thousand Tons/Year	Annualized Cost Thousands of Dollars[c]
None	9.31			
Divided Fuel Supply[b]	7.67	18	1.64	942
Modified compressor air bleed[b]	6.05	35	3.26	547

[a] Assumes a standard commercial airport with 270,000 LTO's in 1979 (based on Los Angeles). Three engine fan jet assumed. Time in various modes used were 70% Taxi/Idle, 20% Approach and 10% Takeoff.

[b] These controls are mutually exclusive.

[c] Los Angeles operations represent approximately 4.1% of air carrier operations. This figure was used to allocate costs. Annualized cost includes annualized portion of capital costs assuming 10% discount rate and 10 year device life plus annual costs. Costs include CO reductions reported in following tables.

Source: Computations based on data in Aircraft Emissions: Impact on Air Quality and Feasibility of Control, U.S. Environmental Protection Agency, p. 14, 60, 69, undated, assumed 1972.

Note: 1972 dollars are assumed in the document. They are inflated to 1973 dollars using the wholesale price indices corresponding to those years.

TABLE F-47. UNIT COST AND EFFECTIVENESS OF CONTROLS APPLIED TO THE EMISSIONS FROM AIRCRAFT PISTON ENGINES[a] (1973 dollars)

Emissions Control	THC Emissions Thousand Tons/Year	Percent Reduction	Change in Emissions[d] Thousand Tons/Year	Annualized Cost Thousands of Dollars[c]
None	35.92			
Air/Fuel Control[b]	17.96	50	17.96	0
Air Injection[b]	17.96	50	17.96	452
Thermal Reactor[c]	8.98	50	8.98	1153
Catalytic Reactor[c]	8.98	50	8.98	1435
Direct Flame Afterburner[c]	3.59	80	14.37	1153
Water Injection[c]	8.98	50	8.98	1051

[a] Assumes standard general aviation airport with 660,000 LTO's/year in 1979 (based on figures for Van Nuys Airport). Single engine aircraft assumed.

[b] These control alternatives are mutually exclusive.

[c] These control alternatives are mutually exclusive and are designed to be used with air/fuel control.

[d] Since, in terms of operations, Van Nuys represents 1.4% of general aviation activity, this figure was used to allocate estimated cost.

[e] Costs include CO reductions reported in next tables.

Source: Computations based on data in Aircraft Emissions: Impact on Air Quality and Feasibility of Control. U.S. Environmental Protection Agency, p. 14, 63, 65, 68, assumed 1972. 1972 dollars have been inflated using wholesale price indices.

TABLE F-48. UNIT COST AND EFFECTIVENESS OF CONTROLS APPLIED TO CARBON MONOXIDE (CO) EMISSIONS FROM AIRCRAFT TURBINE ENGINES[a] (1973 dollars)

Emissions Control	CO Emissions Thousand Tons/Year	Percent Reduction	Change in Emissions Thousand Tons/Year	Annualized[c] Cost Thousands of Dollars
None	6.87			
Divided fuel supply[b]	5.67	17	1.20	942
Modified compressor air bleed[b]	4.46	35	2.41	547

[a] Assumes a standard commercial airport with 270,000 LTO's in 1979 (based on Los Angeles). Three engine fan jet assumed. Time in various modes used were 70% Taxi/Idle, 20% Approach and 10% Takeoff.

[b] These controls are mutually exclusive.

[c] Los Angeles operations represent approximately 4.1% of air carrier operations. This figure was used to allocate costs. Costs include THC reductions reported in preceding tables. 1972 dollars have been inflated using wholesale price indices.

Source: Computations based on data in Aircraft Emissions: Impact on Air Quality and Feasibility of Control, U.S. Environmental Protection Agency, p. 14, 60, 69, assumed 1972.

TABLE B-49. UNIT COST AND EFFECTIVENESS OF CONTROLS APPLIED TO CARBON MONOXIDE (CO) EMISSIONS FROM AIRCRAFT PISTON ENGINES[a] (1973 dollars)

Emissions Control	CO Emissions Thousand Tons/Year	Percent Reduction	Change in Emissions Thousand Tons/Year	Annualized[c] Cost Thousands of Dollars
None	40.12			
Air/Fuel Control	20.06	50	20.06	0
Air Injection[b]	4.01	75	16.05	452
Thermal Reactor[b]	4.01	75	16.05	1153
Catalytic Reactor[b]	4.01	75	16.05	1435
Direct Flame Afterburner[b]	4.01	75	16.05	1153
Water Injection[b]	4.01	75	16.05	1051

[a] Assumes a standard general aviation airport with 660,000 LTO's/year in 1979 (based on figures for Van Nuys Airport). Single engine aircraft assumed.

[b] These control alternatives are mutually exclusive.

[c] Since, in terms of operations, Van Nuys represents 1.4% of general aviation activity, this figure was used to allocate estimated cost. Costs include THC reductions reported in preceding tables. 1972 dollars have been inflated using wholesale price indices.

Source: Computations based on data in Aircraft Emissions: Impact on Air Quality and Feasibility of Control, U.S. Environmental Protection Agency, p. 14, 63, 65, 68, assumed 1972.

TABLE F-50. UNIT COST AND EFFECTIVENESS OF CONTROLS APPLIED TO NITROGEN OXIDE (NO_x) EMISSIONS FROM GAS FUELED UTILITY BOILERS[a] (1973 dollars)

Emissions Control	NO_x Emissions Thousand Tons/Year	Percent Reduction	Change in Emissions Thousand Tons/Year	Annualized Cost Thousands of Dollars
None	48.08			
Low Excess Air (LEA)	32.21	33	15.87	(116)
Two-stage combustion[b]	4.81	85	27.40	0
Fuel gas recirculation[b]	9.62	70	22.59	246
Water Injection	43.27	10	4.81	175

[a] Assumes a standard 1000 megawatt boiler used 6,120 hrs/yr.

[b] These controls are mutually exclusive and are designed to be used with LEA.

Note: Numbers in parentheses represent savings.

Source: Computations based on data in Control Techniques for NO_x From Stationary Sources, Public Health Service, p. 5 - 3 (1970). Costs have been inflated to 1973 dollars using wholesale price indices.

TABLE F-51. UNIT COST AND EFFECTIVENESS OF CONTROLS APPLIED TO NITROGEN OXIDE (NO_x) EMISSIONS FROM OIL-FUELED UTILITY BOILER[a] (1973 dollars)

Emissions Control	NO_x Emissions Thousand Tons/Year	Percent Reduction	Change in Emissions Thousand Tons/Year	Annualized Cost Thousands of Dollars
None	27.22			
Low Excess Air (LEA)	18.23	33	8.99	(363)
Two-stage combustion[b]	7.35	60	10.88	0
Fuel Gas recirculation[b]	8.17	55	10.06	246
Water Injection	24.49	10	2.73	218

[a] Assumes a standard 1000 megawatt boiler used 6120 hrs/yr.

[b] These controls are mutually exclusive and are designed to be used with LEA.

Note: Numbers in parentheses represent savings.

Source: Computations based on data in Control Techniques for NO_x from Stationary Sources, Public Health Service, p. 5 - 3 (1970). Costs have been inflated to 1973 dollars using wholesale price indices.

TABLE F-52. UNIT COST AND EFFECTIVENESS OF CONTROLS APPLIED TO NITROGEN OXIDE (NO_x) EMISSIONS FROM COAL-FIRED UTILITY BOILERS[a] (1973 dollars)

Emissions Control	NO_x Emissions Thousand Tons/Year	Percent Reduction	Change in Emissions Thousand Tons/Year	Annualized Cost Thousands of Dollars
None	27.22			
Low Excess Air (LEA)	20.41	25	6.81	(96)
Two-stage combustion[b]	10.89	47	9.52	364
Fuel gas recirculation[b]	12.25	40	8.16	246
Water Injection[b]	24.49	10	2.73	174

[a] Assumes a standard 1000 megawatt boiler used 6120 hrs/yr.

[b] These controls are mutually exclusive and are designed to be used with LEA.

Note: Numbers in parentheses represent cost savings.

Source: Computations based on data in Control Techniques for NO_x from Stationary Sources, Public Health Service, p. 5 - 3 (1970). Costs have been inflated to 1973 dollars using wholesale price indices.

TABLE F-53. UNIT COST AND EFFECTIVENESS OF CONTROLS APPLIED TO NITROGEN OXIDE (NO_x) EMISSIONS FROM COAL-FIRED INDUSTRIAL BOILER[a] (1973 dollars)

Emissions Control	NO_x Emissions Tons/Year	Percent Reduction	Change in Emissions Tons/Year	Annual Cost	Capital Cost
None	418.85				
Low Excess Air (LEA)	314.14	25	104.71	$ 130	
Fuel gas recirculation[b]	279.23	11	34.91	9,689	$141,000

[a] Assumes a standard boiler producing 190,000 lbs of steam per hour.

[b] Can be used with LEA.

Source: Computations based on data in Analysis of Control Strategies to Attain National Ambient Air Quality Standard for NO_2, J. Crenshaw and A. Basala (1974).

TABLE F-54. UNIT COST AND EFFECTIVENESS OF CONTROLS APPLIED TO NITROGEN OXIDE (NO_x) EMISSIONS FROM STATIONARY INTERNAL COMBUSTION ENGINES[a] (1973 dollars)

Emissions Control[2]	NO_x Emissions Tons/Year	Percent Reduction	Change in Emissions Tons/Year	Annualized[c] Cost
None	49.34			
Mode [b]	26.02	47	23.32	$ 466.50
Mode [b]	20.77	58	28.56	585.75
Mode [b]	28.29	43	21.05	2980.50
Mode [b]	30.88	37	18.46	3079.00
Mode [b]	34.44	30	14.90	2555.50
Mode [b]	17.05	65	32.39	8412.85
Mode [b]	41.31	16	8.03	2161.50
Mode [b]	47.50	4	1.84	746.40

[a] Assumes a standard spark-fired gas engine, 1080 bhp and 300 rpm operated 250 days 12 hrs/day.

[b] These are mutually exclusive controls. The various modes involve timing, manifold temperature, etc. and are described in the source document.

[c] Annualized cost is operating cost.

Source: Computations based on data in Stationary Internal Combustion Engines in the U.S., Environmental Protection Agency, p. 60, (1973). Costs have been inflated to 1973 dollars using wholesale price indices.

TABLE F-55. UNIT COST AND EFFECTIVENESS OF CONTROLS APPLIED TO NITROGEN OXIDE (NO_x) EMISSIONS FROM NITRIC ACID MANUFACTURE[a] (1973 dollars)

Emissions Control	NO_x Emissions Tons/Year	Percent Reduction	Change in Emissions Tons/Year	Annual Cost Thousands of Dollars	Capital Cost
None	2163				
Catalytic Combustion (Natural Gas)[b]	204.1	91	1958.9	13.94	$43,931
Catalytic Combustion (75% Natural Gas & 25% H_2)[b]	40.82	98	2122.18	24.40	43,931
Catalytic Combustion (Hydrogen)[b]	30.62	99	2132.38	55.77	43,931

[a] Assumes a standard model plant producing 326.6 T/Day of Nitric Acid oper operating 250 Days/Yr.

[b] These controls are mutually exclusive.

Source: Computations based on data in Control Techniques for NO_x from Stationary Sources, Public Health Service, p. 7 - 11, (1970). Costs have been inflated to 1973 dollars using wholesale price indices.

APPENDIX G

VALIDATION OF JOINT PROBABILITIES FOR WORK TRIPS PREDICTED BY THE TRANSPORTATION MODULE

While total base year vehicle miles traveled (VMT) by mode is exogenous, the Transportation Module also breaks down the predicted totals by zone within the urban area and by trip purpose. In this appendix we validate the work-trip breakdown in Table G-1 against the MATHAIR outputs reported in Tables G-2 through G-5.

TABLE G-1. CHOICE OF WORK TRIP TRANSPORTATION MODE (1970)

	% of Employed Central City Residents Using:		% of Employed Non-Central City Residents Using:	
	Auto	Transit	Auto	Transit
New York	30	70	82	18
Chicago	60	40	88	12
Washington, D.C.	57	43	91	9
Los Angeles	90	10	97	3

Source: Calculated from AIP-MVMA, Urban Transportation Factbook (1974), p. I-22, assuming that all work trips use either automobile or mass transit.

For New York, for example, Table G-3 shows that about 30 percent of the work trips originating in the center are taken by automobile, as are about

80 percent of those originating outside the central city. * These numbers compare favorably with the first line of Table G-1. A similar analysis may be made for work trips in the other urban areas.

---

* For example, we calculate that in New York 80% of the trips originating outside the center of the city are taken by automobile in the following way:

$$\left[(.942 \times 3,270,000) + (.430 \times 1,230,000)\right] / 4,500,000 = .802 = 80.2\%$$

where .942 = joint probability for using the automobile for work trips entirely within the suburbs

3,270,000 = the number of potential work trips entirely within the suburbs

.430 = joint probability for using the automobile for work trips from the suburbs to the center of the city

1,230,000 = the number of potential work trips from the suburbs to the center of the city (and 3,270,000 + 1,230,000 = 4,500,000)

All figures are shown in Table G-3.

TABLE G-2. JOINT PROBABILITY PREDICTIONS FOR LOS ANGELES

Joint Probabilities For Automobile

	C-C-C	S-S-S	C-S-C	S-C-S
Work	.945	.981	.961	.982
Shop	.869	.872	.670	.675
Other	.673	.675	.499	.502

Joint Probabilities For Bus

	C-C-C	S-S-S	C-S-C	S-C-S
Work	.055	.019	.039	.018
Shop	.006	.003	.013	.007
Other	.017	.014	.010	.005

Joint Probabilities For Rail

	C-C-C	S-S-S	C-S-C	S-C-S
Work	.0	.0	.0	.0
Shop	.0	.0	.0	.0
Other	.0	.0	.0	.0

Potential Trips in The Areas (millions)

	C-C-C	S-S-S	C-S-C	S-C-S
Work	.85	1.61	.30	.74
Shop	1.20	2.12	1.20	2.12
Other	1.20	2.12	1.20	2.12

C-C-C	trips within center
S-S-S	trips within suburb
C-S-C	round-trips from center to suburb
S-C-S	round-trips from suburb to center

Source: MATHAIR output

TABLE G-3. JOINT PROBABILITY PREDICTIONS FOR NEW YORK

Joint Probabilities For Automobile

	C-C-C	S-S-S	C-S-C	S-C-S
Work	.315	.942	.273	.430
Shop	.400	.945	.442	.190
Other	.000	.774	.327	.111

Joint Probabilities For Bus

	C-C-C	S-S-S	C-S-C	S-C-S
Work	.269	.015	.328	.235
Shop	.002	.000	.000	.000
Other	.011	.000	.000	.000

Joint Probabilities For Rail

	C-C-C	S-S-S	C-S-C	S-C-S
Work	.416	.043	.399	.335
Shop	.118	.000	.041	.008
Other	.105	.000	.001	.003

Potential Trips in The Areas (millions)

	C-C-C	S-S-S	C-S-C	S-C-S
Work	2.71	3.27	.10	1.23
Shop	2.84	3.70	2.84	3.70
Other	2.84	3.70	2.84	3.70

C-C-C	trips within center
S-S-S	trips within suburb
C-S-C	round-trips from center to suburb
S-C-S	round-trips from suburb to center

Source: MATHAIR output

TABLE G-4. JOINT PROBABILITY PREDICTION FOR WASHINGTON, D. C.

Joint Probabilities For Automobile

	C-C-C	S-S-S	C-S-C	S-C-S
Work	.569	.906	.958	.903
Shop	.823	.926	.800	.655
Other	.875	.923	.937	.910

Joint Probabilities For Bus

	C-C-C	S-S-S	C-S-C	S-C-S
Work	.431	.094	.042	.092
Shop	.052	.007	.044	.106
Other	.031	.020	.011	.021

Joint Probabilities For Rail

	C-C-C	S-S-S	C-S-C	S-C-S
Work	.0	.0	.0	.0
Shop	.0	.0	.0	.0
Other	.0	.0	.0	.0

Potential Trips in The Areas (millions)

	C-C-C	S-S-S	C-S-C	S-C-S
Work	.219	.257	.053	.129
Shop	.259	.334	.259	.254
Other	.259	.334	.259	.254

C-C-C	trips within center
S-S-S	trips within suburb
C-S-C	round-trips from center to suburb
S-C-S	round-trips from suburb to center

Source: MATHAIR output

TABLE G-5. JOINT PROBABILITY PREDICTIONS FOR CHICAGO

Joint Probabilities For Automobile

	C-C-C	S-S-S	C-S-C	S-C-S
Work	.564	.929	.718	.665
Shop	.867	.885	.589	.584
Other	.731	.826	.539	.605

Joint Probabilities For Bus

	C-C-C	S-S-S	C-S-C	S-C-S
Work	.117	.071	.108	.114
Shop	.007	.003	.039	.026
Other	.002	.008	.055	.033

Joint Probabilities For Rail

	C-C-C	S-S-S	C-S-C	S-C-S
Work	.319	.0	.174	.221
Shop	.003	.0	.040	.027
Other	.077	.0	.105	.065

Potential Trips in The Areas (millions)

	C-C-C	S-S-S	C-S-C	S-C-S
Work	.980	1.04	.205	.372
Shop	.990	1.28	.990	1.28
Other	.990	1.28	.990	1.28

C-C-C	trips within center
S-S-S	trips within suburb
C-S-C	round-trips from center to suburb
S-C-S	round-trips from suburb to center

Source: MATHAIR output

APPENDIX H

MATHAIR USER DOCUMENTATION

All MATHAIR programs and data are stored as files on an IBM 371-68, accessed through the NCSS time-sharing computer network. A listing and a card deck of all programs and data are being submitted under separate cover to the Project Officer.

Four types of files are needed for a simulation run:

- control commands
- MATHAIR programs
- strategy description
- input data

In addition, MATHAIR generates two output data files.

While MATHAIR consists of six functional modules, it is stored as four subroutines in the following FORTRAN files:

- AIR
- READEM
- NMILES
- DG

DG is the Benefits Module subroutine. If the user wishes to provide his own benefits module, DG should be replaced by another subroutine of the same name.

For each simulation, five input files, two strategy files, and two output files must be specified. The files that we have used to test MATHAIR are named and described in Figure H-1. Figure H-2 shows the control language files which contain specifications of all the files need for one simulation.

RUNNING THE MATHAIR MODEL

In order to run MATHAIR, the following preparations must be made.

1. Several keywords in the input files must be set:

Number	Los Angeles		New York		Chicago		Washington, D.C.	
	File Name	File Type	File Name	File Type	File Name	File Type	File Name	File Type
1	LA	DATA	NY	DATA	CH	DATA	DC	DATA
2a*	LEM75	DATA	EM75	DATA	EM75	DATA	EM75	DATA
b	LEM74	DATA	EM74	DATA	EM74	DATA	EM74	DATA
c	LEM65	DATA	EM67	DATA	EM67	DATA	EM67	DATA
3	LA-DEV	DATA	ALL-DEV	DATA	ALL-DEV	DATA	ALL-DEV	DATA
4	LA-IN	DATA	NY-IN	DATA	CH-IN	DATA	DC-IN	DATA
5	DAMLA	DATA	DAMNY	DATA	DAMCH	DATA	DAMDC	DATA
6a*	A65	STRATEGY	A67	STRATEGY	A67	STRATEGY	A67	STRATEGY
b	A74	STRATEGY	A74	STRATEGY	A74	STRATEGY	A74	STRATEGY
c	L75	STRATEGY	A75	STRATEGY	A75	STRATEGY	A75	STRATEGY
d	L75IM	STRATEGY	A75IM	STRATEGY	A75IM	STRATEGY	A75IM	STRATEGY
e	LFULL	STRATEGY	AFULL	STRATEGY	AFULL	STRATEGY	AFULL	STRATEGY
7a*	SNULL	STRATEGY	SNULL	STRATEGY	SNULL	STRATEGY	SNULL	STRATEGY
b	SHALF	STRATEGY	SHALF	STRATEGY	SHALF	STRATEGY	SHALF	STRATEGY
c	SFULL	STRATEGY	SFULL	STRATEGY	SFULL	STRATEGY	SFULL	STRATEGY
8	PR	DATA	PR	DATA	PR	DATA	PR	DATA
9	LAOUT	DATA	NYOUT	DATA	CHOUT	DATA	DCOUT	DATA

* In categories 2, 6, and 7, one of the set of files must be selected.

Number	Description of File Contents
1	General information about the respective urban areas.
2	Emissions information (which is the same for all areas except Los Angeles).
a	It is assumed that post-1975 vehicles have 1975 emission characteristics.
b	It is assumed that post-1974 vehicles have 1974 emission characteristics.
c	It is assumed that post-1967 vehicles have 1967 emission characteristics (1965 for Los Angeles).
3	Descriptions of new and retrofit devices for automobiles.
4	Input to transportation submodel.
5	Input to damage submodel.
6	Strategy for auto pollution control.
a	It is assumed that post-1967 vehicles have 1967 characteristics (1965 for Los Angeles).
b	It is assumed that post-1974 vehicles have 1974 characteristics.
c	It is assumed that post-1975 vehicles have 1975 characteristics.
d	Same as 6c: also inspection and maintenance required for all vintages.
e	Same as 6d: also post-1977 vehicles required to meet interim-1978 standards and a set of retrofit devices are required.
7	Strategy for stationary source pollution control.
a	No controls required.
b	Light control.
c	Strict control.
8	Output of the transportation model.
9	Output file.

Figure H-1. MATHAIR input and output files

Number	Los Angeles		Other Regions	
	File Name	File Type	File Name	File Type
1	LA1	EXEC	S1	EXEC
2	LA2	EXEC	S2	EXEC
3	LA3	EXEC	S3	EXEC
4	LA4	EXEC	S4	EXEC
5	LA5	EXEC	S5	EXEC

Number	Emission and Strategy Files Used (See Figure H-1 for descriptions)
1	uses LEM65 (EM67), A65 (A67) SNULL
2	uses LEM74 (EM74), A74, SHALF
3	uses LEM75 (EM75), L75 (A75), SFULL
4	uses LEM75 (EM75), L75IM (A75IM), SFULL
5	uses LEM75 (EM75), LFULL(AFULL), SFULL and assumes transportation times and costs within LA-IN (CH-IN, etc.) may have been altered

For example, LA1 EXEC is as follows:

```
FILEDEF 3 DSK SNULL STRATEGY
FILEDEF 12 DSK A67 STRATEGY
FILEDEF 5 DSK LA DATA
FILEDEF 15 DSK LEM67 DATA
FILEDEF 10 DSK LA-DEV DATA
FILEDEF 7 DSK LAOUT DATA
FILEDEF 8 DSK LA-IN DATA
FILEDEF 16 DSK PR DATA RECFM FA LRECL 133
          BLKSIZE 133
FILEDEF 1 DSK DAMLA DATA RECFM FA LRECL 133
          BLKSIZE 133
```

Figure H-2. MATHAIR control language

- ISW (in LA DATA) must have one of the following values:
  - 0 if the transporation model is to predict VMT.
  - 1 if exogenous VMT is specified.
- ALPHA and BETA (in LA DATA):
  - ALPHA: five stationary source coefficients for air quality model.
  - BETA: model source coefficients. Presently two sets of coefficients have been calibrated ($\alpha = \beta$ and $\alpha' = 100 \times \beta'$). The user should be sure the desired values have been assigned.
- TERM (in LA DATA) - number of years for which model is to run.
- KFLAG (in LA DATA) must have one of the following values:
  - 0 if intermediate transportation output is not desired.
  - 1 if PR DATA is desired.
- MFLAG (in LA-IN DATA) must have one of the following values:
  - 0 if only the transportation model is to be run.
  - 1 the general case where the whole model is run.
- IFLAG (in DAMIN DATA) must have one of the following values:
  - 0 if no mobile or stationary source control devices are to be simulated (i.e., base case for damages).
  - 1 if some strategy is being implemented.

2. The FILEDEF commands in the EXEC files must correspond to the files for a given simulation. In particular:

FILEDEF 12	for appropriate mobile strategy file.
FILEDEF 3	for appropriate stationary strategy file.
FILEDEF 15	for appropriate emissions file.

Also, the proper city name must appear in all places: for example, CH DATA must be changed to NY DATA if a simulation for New York is desired.

Only two commands are necessary to execute the model:

XX, where XX is one of S1, . . . , S5, LA1, . . . , LA5

and

```
RUN AIR READEM NMILES DG.
```

The first command executes the control language file which identifies the input and output files. The second command loads and runs compiled versions of the four MATHAIR modules.

Output is stored as disk files. Output files may be either edited and/or printed at the terminal or else offline printed as in the following example for Los Angeles:

```
TITLE LA NULL STRATEGY (optional--generates
   a cover page)
```

```
OFFLINE PRINT LAOUT DATA
```

MATHAIR INPUT FILE DESCRIPTIONS

In the following section, we give a detailed description of form of the five input files for Los Angeles. Each line of each input files begins with a keyword of ten characters or less, and the keyword is followed by one or more numbers. MATHAIR does not read the keyword.

In the following pages, each line of each input file is described in three ways:

- the MATHAIR format that is used to read it
- the keyword
- a description of the inputs that follow the keyword

NAME OF FILE: LA DATA

Format	Keyword	Description
20A4	(no keyword)	name of urban area (or other title)
10X, I2	ISW	0 if transportation model is to predict VMT 1 if exogenous VMT is to be used
10X, 3I5	OYRIYRTER	3 variables: • year of oldest vintage car in stock to be described • present year (base year for model) • term of model

Format	Keyword	Description
10X, 3E10. 3	DVMT	daily VMT: auto, bus, train
10X, 7E10. 3	AUTOREGS	number of new car registrations from present year back to year in which oldest vintage car was new (7 to a line)
10X, F10. 3	AUTOGROW	rate at which new car registrations will grow in the future
10X, 7E10. 3	AMILE	average number of miles a year driven by cars of successively greater age for all ages in stock
10X, 7F10. 3	AJUNK	1 - scrappage rate of cars of successively greater age for all ages in stock
10XF5. 2	DR	discount rate
10X, I5	IPOL	number of pollutants besides sulfur and lead (i. e., always three in present model)
10X, I5	IAGE	number of years provided for aging of a vehicle in deterioration factors
10X, I5	NYR	number of vintage years for deterioration factors
10X, F5. 2	SPEED	average auto speed (weighted by relative frequency of different purpose trips)
10X, F5. 2	HCDIURN	daily diurnal HC loss per auto
10X, 3F5. 2	SULF	SO_x emissions per VMT (auto, bus, train)
10X, 3F5. 2	BUSEM	bus emissions per VMT of CO, HC, NO_x
10X, F5. 2	LEAD1975	gr. lead/gal. fuel (1975)
10X, F5. 2	LEAD1976	gr. lead/gal. fuel (1976)
10X, F5. 2	LEAD1977	gr. lead/gal. fuel (1977)
10X, F5. 2	NONLEAD1975	% cars requiring non-leaded gasoline (1975)

Format	Keyword	Description
10X, F5.2	NONLEAD1974	% cars requring non-leaded gasoline (1974)
10X, F5.2	NONLEAD1973	% cars requring non-leaded gasoline (1973)
10X, F5.2	NONLEAD1972	% cars requring non-leaded gasoline (1972)
10X, F5.2	NONLEAD1971	% cars requring non-leaded gasoline (1971)
10X, 5F10.0	MTC	motorcycle emissions (CO, HC, NO_x, SO_x, Pb)
10X, 5F10.0	GROWTH	annual growth rate for motorcycle emissions
10X, 5F10.0	MHDDF	heavy-duty diesel emissions
10X, 5F10.0	GROWTH	annual growth rate for heavy-duty diesel emissions
10X, 5F10.0	MHDG	heavy-duty gasoline emissions
10X, 5F10.0	GROWTH	annual growth rate for heavy-duty gasoline emissions
10X, 5E10.2	ALPHA	stationary source coefficients for air quality
10X, 5E10.2	BETA	mobile source coefficients
10X, 2E10.2	XYZ	coefficients for alternative OX models
10X, 10I5	NUMBSO	number of installations for n ($n \leq 10$) kinds of stationary sources
20A4	name 1	name of first source (at a typical installation)
10X, 5F10.0	name 1	emissions of first source (CO, HC, NO_x, SO_x, Pb)
10X, 5F10.0	GROWTH	annual growth rate for name 1
	⋮	⋮
20A4	name$_n$	name of nth source

Format	Keyword	Description
10X, 5F10.0	$name_n$	emissions of nth source
10X, 5F10.0	GROWTH	annual growth rate for name n
10X, I5	NUMBDE	number of control devices to be described
20A4	$name_1$	name of first control device
10X, 5F5.2, 2E10.4	$SDEV_1$	proportion by which it reduces the five pollutants; installation cost, annual maintenance
	⋮	⋮
20A4	$name_{NUMBDE}$	name of last device
10X, 5F5.2, 2E10.4	$SDEV_{NUMBDE}$	characteristics of last device

NAME OF FILE: LAEMIS DATA

10X, 10F5.2	DETCO1975 ⋮ DETHC1975	deterioration factors for autos of named vintage (NYR vintage) for given pollutant when car is new, 1 year old, . . . , up to IAGE years old
	⋮	⋮
10X, 10F5.2	DETNOX1965	up to IAGE years old
10X, 10F5.2	FDETCO76+ FDETHC76+ FDETNOX76+	deterioration factors for the CO and HC in years 1976 and later and for NO_x in 1977 and later
10X, 10F5.2	FDETNOX76	deterioration factors for NO_x in 1976
10X, 4F5.2	EMIS1975	emissions of CO, HC, NO_x from auto of given vintage and running and hot soak (HC) loss (gr./mi.)
	⋮	⋮
10X, 4F5.2	EMIS1975	
10X, 4F5.2	FEMIS1976	same for autos of given (future) vintages
	⋮	⋮
10X, 4F5.2	FEMIS1985	

NAME OF FILE: LA-DEV DATA

Format	Keyword	Description
10X, A6, 8X, I4	DEVICE	name of auto pollution control device and vintage of auto
10X, 10F7.2	CO	% reduction in CO emissions for new cars, one-year old, up to IAGE years old
10X, 10F7.2	HC	% reduction in HC emissions
10X, 10F7.2	NOX	% reduction in NO_x emissions
10X, 3F7.2	COST	installed cost; annual costs in lost fuel and in maintenance

Devices are described by consecutive sets of five cards each. The file should terminate with a blank card (indicating that there are no more devices).

NAME OF FILE: DAMLA DATA

10X, I2	NCAT	number of damage categories to be used (≤ 8). Currently ncat = 3
2A4	CAT_1	name of first category (health)
2A4	CAT_2	name of second category (vegetation)
2A4	CAT_{ncat}	name of last category (materials)
10X, I2	IFLAG	not used
10X, 5E10.4	DAMHEALTH	\$ value in base year of damage to health by CO, OX, NO_x, SO_x, Pb
10X, 5E10.4	DAMPLANT	same for damage to vegetation
10X, 5E10.4	DAMMATER	same for damage to materials
10X, 5F10.4	CBASEHEALT	concentration in ppm (mg/m^3 per Pb) of pollutant causing base year damage to health
10X, 5F10.4	CBASEPLANT	same for vegetation
10X, 5F10.4	CBASEMATER	same for materials
10X, 5F10.4	DGROWHEALT	annual growth rate of base year damage to health assumed at unchanged pollutant concentration

10X, 5F10.4	DGROWPLANT	same for vegetation
10X, 5F10.4	DGROWMATER	same for material
10X, 5F10.4	EXPOHEALTH	exponent in health damage function (one for each pollutant)
10X, 5F10.4	EXPOPLANT	same for vegetation
10X, 5F10.4	EXPOMATER	same for materials
10X, 5F10.4	THRESHHEAL	threshold concentration below which no health damage occurs (one for each pollutant)
10X, 5F10.4	THRESHPLAN	same for vegetation
10X, 5F10.4	THRESHMATE	same for materials

NAME OF FILE: LA-IN DATA

10X, I2	MFLAG	0: transportation model only is run 1: full model is run
10X, I2	KFLAG	0: PR DATA output file is abbreviated 1: full details in PR DATA
10X, 2E12.4	POP	1975 center-city and suburban population estimates
10X, 2F7.0	POPGRO	center-city and suburban population growth factors
10X, 6F7.0	POPFAC	factors used to generate potential trips from center-city and suburb, by purpose
10X, 9F7.0	AVDIST	average travel distance by purpose and area for each mode
10X, 6F7.0	AB^{G}	regression coefficients for mode-split equations
10X, 6F7.0	ABGX	regression constraints for mode-split equations
10X, 6F7.0	DELLAM	parameters of trip frequency equation
10X, I2	M	flag for execution control (default M=1)

Format	Keyword	Description
10X, 6F7.0	AIV	automobile in-vehicle time
10X, 6F7.0	ACT	fixed cost of auto trip (parking, etc.)
10X, 6F7.0	ACM	auto costs per mile (fuel and operating)
10X, 6F7.0	BUSFAR	bus fare
10X, 6F7.0	TWWB	waiting and walking time for bus trip
10X, 6F7.0	TSSB	station-to-station riding time for bus trip
10X, 6F7.0	RAIFAR	rail fare
10X, 6F7.0	TWWR	waiting and walking time for rail trip
10X, 6F7.0	TSSR	station-to-station riding time for rail trip
10X, 3F7.0	AOGL	auto occupancy level by trip purpose
10X, 3F7.0	AOB	bus occupancy level by trip purpose
10X, 3F7.0	AOR	rail occupancy level by trip purpose
10X, 2F7.0	AVOT1, AVOT2	average value of time spent waiting and riding
10X, F7.0	NBUS	number of buses in initial year
10X, F7.0	BCAP	acquisition cost of a bus
10X, F7.0	BMAINT	maintenance per bus-mile
10X, 3F7.0	COR	correction factors for auto, bus, rail VMT as output by transportation model
10X, 2F7.0	CSI, CSJ	mesh descriptors for approximation of consumer surplus integral (suggested values: CSI = 5 and CSJ - .5)

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/5-76-010
2.
3. RECIPIENT'S ACCESSION NO.

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16. ABSTRACT

This report describes MATHAIR, a computer model that simulates the impacts of strategies for controlling mobile source air pollutants. Vehicle miles traveled (VMT) for different modes of ground transportation are predicted by a transportation module. Given VMT predictions, an inventory of stationary sources of mobile source pollutants and certain other inputs for the urban area, pollutant emissions are calculated using EPA-developed relations. A linear rollback air quality module then predicts ambient pollutant concentrations. Finally strategy costs and benefits due to damage reduction are calculated.

A set of experiments were performed for four selected urban regions using MATHAIR. MATHAIR casts all strategy costs (including the imputed social cost of trips foregone or induced by a strategy) and all benefits in dollar terms so that strategies can be compared in terms of their total impact. A baseline, zero control strategy and four strategies of increasing stringency are defined and simulated over a ten-year horizon. One general conclusion suggested by the results of the test is that it is economically inefficient to impose the same program of controls in different urban regions. Another conclusion is that the control strategies are very sensitive to certain input data.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution Benefit/cost analysis Economic analysis Economic effects Econometric models Automotive Transportation models	Environmental Economics Air Pollution Economics Automobile Pollution Environmental Modeling Benefit/cost analysis	05C Behavioral and Social Science/ Economics

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